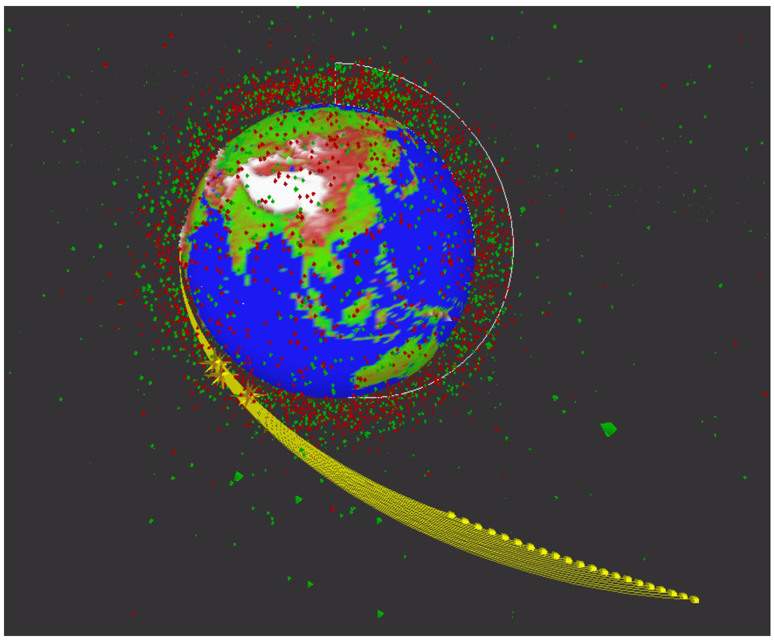
SMC Orbital/Sub-Orbital Hazards and Debris Mitigation User's Handbook



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SMC ORBITAL/SUB-ORBITAL DEBRIS MITIGATION USER'S HANDBOOK

Version 1.0

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Ms. Frankie Shelton (SMC/AXFV), Dr. William Ailor, Dr. Richard Baker, Jorge Beraun (AFRL/DELE), Rolf Bohman, James Gidney, Robert Gist, Dr. Charles Griffice, Alan Jenkin, Dr. Valerie Lang, Kenneth Luey, Benjamin Mains, Daniel Oltrogge, Dr. Russell Patera, Dr. Glenn Peterson, and Dr. Keith Zondervan.

Contents

1. Introduction

1.1 Purpose

The purpose of this handbook is to provide Space and Missile Systems Center (SMC) space system developers a reference for use in satisfying DoD and National Space Policy regarding the Mitigation and Control of space debris[1]. Meeting policy objectives involves mitigation of the effects of the debris environment on military space systems as well as mitigation of the effects of military space systems on other users of space. This handbook is intended to be a source of information to assist space system developers, planners, and operators in mitigating the effects of debris to assure minimal impact on their systems and on other users of space through proper design and operations. In addition, this handbook acquaints SMC space system developers with the various types of space hazards as well as current debris mitigation practices of SMC space programs. Metrics for determining the cost effectiveness of mitigation measures will be developed for inclusion in later versions of the handbook.

1.2 Definition

In this document, the term debris refers to both orbital (or space) debris and sub-orbital debris. Space debris is defined as any non-functioning man-made object orbiting the Earth. This definition distinguishes space debris from functioning operational payloads and natural meteoroids that pass through the Earth's orbit. The intention is to classify debris as all objects which pose a collision hazard but which cannot be easily or feasibly controlled to reduce the hazard they pose. Historically, the space debris environment is a product of launched objects (including satellites, spent stages, and operational debris) and fragments from on-orbit breakups. Recently there has been evidence of new sources that result from objects deteriorating in orbit; in the future, with the projected increase in space traffic, there is a growing potential for on-orbit collisions[2]. Figure 1-1 portrays the number and type of debris objects greater than 10 cm that were in orbit at any time during any particular year from 1957 to 2000.

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[1] The National Space Policy, 14 September 1996, states that:

"The United States will seek to minimize the creation of space debris. NASA, the Intelligence Community, and the DoD, in cooperation with the private sector, will develop design guidelines for future government procurements of spacecraft, launch vehicles, and services. The design and operation of space tests, experiments, and systems will minimize or reduce accumulation of space debris consistent with mission requirements and cost effectiveness.

It is in the interest of the US Government to ensure that space debris minimization practices are applied by other spacefaring nations and international organizations. The US Government will take a leadership role in international fora to adopt policies and practices aimed at debris minimization and will cooperate internationally in the exchange of information on debris research and the identification of debris mitigation options."

[2] An excellent source of background information is the Interagency Report on Orbital Debris by the Office of Science and Technology Policy, November 1995. The document can be found on the World Wide Web at http://www-sn.jsc.nasa.gov/debris/report95.html.

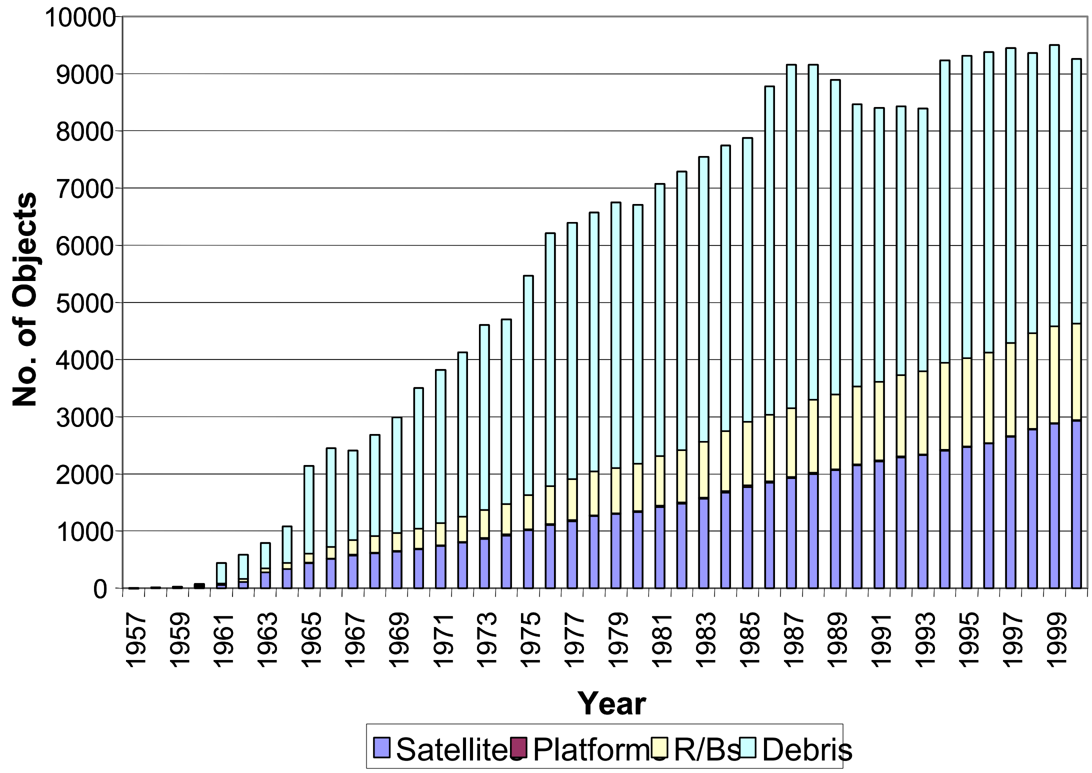

Figure 1-1. Orbiting man-made objects.

Sources of debris are the target of debris mitigation options. In a broad sense, debris mitigation involves methods to minimize production of debris, methods to protect spacecraft during operations within the orbital debris environment, and methods to remove debris from orbit. DoD debris mitigation practices have evolved in concert with NASA, perhaps most notably in preventing Delta rocket body breakups.[3]

NASA/JSC has developed a strategy[4] for space programs to mitigate debris hazards by controlling the program's energy contribution to the orbital debris environment. The first step is to manage stored chemical and mechanical energy within a spacecraft. This requires reliable designs to prevent explosions during operations as well as after operations are completed to vent or deplete residual energy such as pressure, fuel, or mechanical energy.

Long term environment management requires removal of objects from useful orbit regimes at the end of mission life; this carries the implicit requirement that objects have sufficient reliability to prevent generation of orbital debris and to ensure they can be disposed of at the end of mission life.

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[3] The original Delta Program office was at NASA GSFC. In May 1981, it was noted that pieces from Delta second stage explosions made up about 27% of the tracked objects with orbital periods under 225 minutes. That same month, GSFC notified McDonnell Douglas Space Systems Company of the explosions and asked that the cause be determined. Ref.: Portee and Loftus, "Orbital Debris: A Chronology," NASA/TP-1999-208856, Jan 99.

[4] NASA Safety Standard NSS 1740.14, Guidelines and Assessment Procedures for Limiting Orbital Debris, August 1995.

1.3 Scope

This document is intended to provide an overview of current SMC debris practices and to provide recommendations on ways to comply with the various debris mitigation and control policies and guidelines.

1.4 Background – Policies/Guidelines

The National Space Policy, signed by the President on 5 January 1988, recognized that man-made orbital debris was rapidly becoming a potential hazard and directed that the creation of space debris be minimized. In addition, the policy mandated that an Interagency Group (IG) Space Working Group provide recommendations for the implementation of the debris minimization section of the policy that states: " . . . all space sectors will seek to minimize the creation of space debris. Design and operation of space tests, experiments, and systems will strive to minimize or reduce accumulation of space debris consistent with mission requirements and cost effectiveness."

The current National Space Policy (PDD-NSC-49/NSTC-8, 19 September 1996) expanded upon the orbital debris description as follows:

"The United States will seek to minimize the creation of space debris. NASA, the intelligence Community, and the DoD, in cooperation with the private sector, will develop design guidelines for future government procurements of spacecraft, launch vehicles, and services. The design and operation of space tests, experiments and systems, will minimize or reduce the accumulation of space debris consistent with mission requirements and cost effectiveness."

Air Force Instruction 91-202, dated 1 August 1998, Safety, The US Air Force Mishap Prevention Program, Chapter 11 Space Safety, Paragraph 11.2 Space Safety Program, states that all units conducting space-related missions must have a comprehensive space safety program consisting of both launch and orbital safety. Space safety programs must be tailored to meet both mission and safety requirements. Safety operations within the space environment are only possible if positive mishap prevention programs are established and faithfully followed.

SMC fully concurs that man-made orbital debris is a growing hazard and that steps are required now to contain the hazard to acceptable levels in the future. SMC already practices debris abatement to a great extent; however, there is concern that some of the recommended practices can cause major increases in cost or place onerous constraints on important military missions. Consequently, before any potential solutions become policy, it is imperative that the full extent of the hazard posed by space debris, alternatives for debris control, cost effectiveness, and mission implications be fully understood.

The initial HQ USAF request for comments on orbital debris resulted from the signing of the National Space Policy and the AF Scientific Advisory Board (SAB) report on orbital debris5. SMC (Lt. Gen. A. Casey) responded with suggested recommendations in a 7 March 1986 letter to AFMC/CC. Prior to the current National Space Policy, an interagency working group received tasking in July 1988 to support the preparation of a report on orbital debris as mandated by the 5 January 1988 National Space Policy implementation directives. SMC/CV responded with a message expressing concern over the tight report preparation schedule and for the potential implications to SMC space programs. Agreement was reached with HQ AFMC to support the interagency working group's request with informal inputs throughout their schedule and work toward a coordinated Space and Missile Systems Center input. The SMC-provided information was a substantial contribution to the 1989 Interagency Group (Space) Report on Orbital Debris. That report called for joint NASA-DoD actions that resulted in cooperative efforts to monitor and

[5] "Special Report of the USAF Scientific Advisory Board Ad Hoc Committee on Current and Potential Technology to Protect Air Force Systems From Current and Future Debris," December 1987.

characterize the orbital debris environment; SMC/XR developed a Commander's Policy for debris mitigation; and AFRL (then the Phillips Laboratory) with AFSPC published a report on the results of the USAF Space Debris Phase One Study.

The 1995 Interagency Report on Orbital Debris (referenced above in section 1.2) provided an update of actions taken as a result of the 1989 report and made recommendations that included having NASA and DoD jointly develop draft design guidelines "that could serve as a baseline for agency requirements for future spacecraft and launch vehicle procurements." The resulting U.S. Government debris mitigation standard practices6 were adapted from the NASA guidelines in coordination with DoD, the Department of Commerce, and the Department of Transportation. Since the presentation of the US Government standard practices to the aerospace industry in January 1997, they have been incorporated in the DoD Instruction for Space Support, Federal Aviation Administration and Federal Communications Commission rules, and other documents listed below:

a) National Reconnaissance Office Satellite Debris Mitigation – Design Guidelines, NROI 82-2, 6 Jan 99
b) National Reconnaissance Office Satellite Debris Mitigation – End of Life, NROI 82-3, 6 Jan 99
c) National Reconnaissance Office Satellite Debris Mitigation Policy, NROI 82-6, 6 Jan 99
d) Satellite Disposal Procedures, UPD10-37, 3 Nov 97
e) 2002 draft revision to Chapter 11 of Air Force Instruction 91-202, Safety, The U.S. Air Force Mishap Prevention Program

[6] US Government Orbital Debris Mitigation Practices. Reference "MEO/LEO Constellations: U.S. Laws, Policies, and Regulations on Orbital Debris Mitigation," AIAA SP-016-2-1999, pp. 5-7.

2. Debris Hazards Associated with Orbit Operations and Tests

The principal debris hazards associated with orbit operations are collisions and erosion of spacecraft surfaces. As part of the DoD-NASA Joint Workplan on Orbital Debris, an Air Force Research Laboratory (AFRL) – Aerospace Corporation team developed a report (TBS) on recommendations for assessing the hazard from debris for DoD spacecraft. The primary objective of this report on debris hazard assessment methodology is to provide guidance to DoD space systems developers and supporting contractors in determining the mission impacts from operating in the space debris environment. Additionally, although debris limitation is not the primary thrust of this report, it discusses compliance approaches with U.S. national policy and guidelines for debris mitigation.

The model used in this report for the prediction of debris environments is ORDEM 96 – developed at the Johnson Space Flight Center. This model is recommended by NASA and is the *de facto* standard in the U.S. An upgrade to this model called ORDEM2000 is expected shortly and may be used in future versions of this report. ORDEM2000 will be more user friendly, but its predictions are not expected to change substantially from those of ORDEM96.

Executable code can be downloaded by visiting the NASA/JSC debris website,

http://www.orbitaldebris.jsc.nasa.gov/model/modeling.html,

clicking on "Modeling", and then following instructions.

Complete documentation on ORDEM96 can be found at the following url:

http://www.orbitaldebris.jsc.nasa.gov/model/ordem96/ordem96a_cont.html

A comparison of ORDEM predicted debris flux with measurements data is in Figure 2-1, courtesy of NASA Johnson Space Center's Orbital Debris Program:

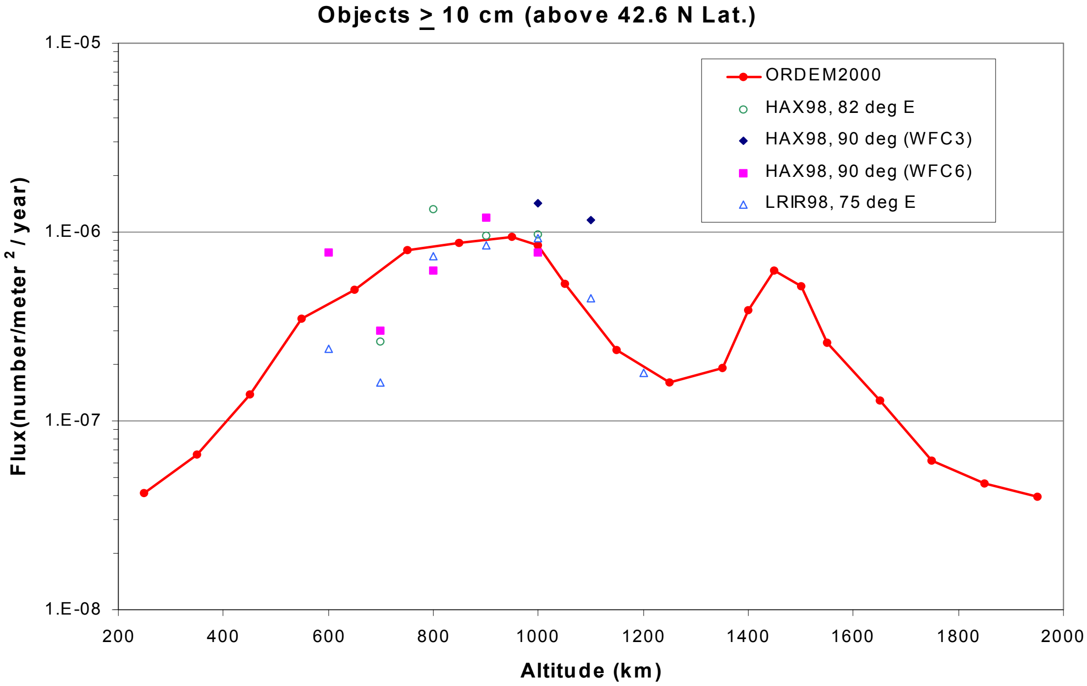

Figure 2-1. Predicted vs. Measured Debris Flux.

3. SMC Debris Mitigation and Control Guidelines

All SMC space programs and projects shall comply with the debris mitigation requirements specified in DoD and AF instructions and as incorporated by reference in SMC Space Flight Worthiness Certification Criteria. An SMC Debris Mitigation Requirements Document that was drafted from the U.S. Government Orbital Debris Mitigation Practices (as adopted in the 2000 draft revision of AFI 91-202) was reviewed by the SMC Program Offices. The results from that review are used in Section 4 to guide the discussion of debris control measures and mitigation options. SMC responsibilities include the use of engineering and operational approaches during system design to minimize debris generation and the provision of capabilities for disposal of systems at end of mission life. Establishment of a Debris Mitigation Implementation Plan and Debris Mitigation OPR are options for consideration. Debris mitigation plans shall be incorporated in design reviews and included as an element in the SMC Space Flight Worthiness Review. Any decision to deviate from the mitigation requirements shall be based on a risk/benefit analysis and shall require the approval of the SMC Chief Engineer.

3.1 Hazard Identification

All SMC space programs must identify any hazards listed in Appendix A that apply to a proposed system. Known hazards associated with the system in the space environment must be evaluated and then either eliminated or controlled. Adequate evidence must be provided that their systems and associated experiments meet the requirements specified in AFI 91-202.

3.2 Hazard Analysis and Risk Assessment

Hazard analyses and associated risk assessments must be conducted on identified operations or failures that could result in hazardous conditions (e.g., non-fail-safe automated operations, the release of energy or mass, or de-stabilization) that cannot be controlled or mitigated. Risk assessments must use models that are proven and represent the hazard being analyzed or the user must provide a mutually agreed upon model with applicable input data. When appropriate, probabilistic risk assessments are used to provide the basis for management decisions. An example of a Reentry Risk Assessment that was performed for a Delta II Stage 2 is provided in Appendix B.

3.3 Monitoring and Tracking Hazard Controls

The monitoring and tracking of hazard controls should be integral to SPO mission assurance and system safety functions. Assessment of the effectiveness of controls and compliance with the National Environmental Protection Act (NEPA) are functions of the SMC Chief Engineer (SMC/AX).

3.4 Program Office Analysis Responsibility

The analysis required to mitigate space debris supports design activities that minimize debris generation, either released during normal operations or caused by accidental explosions, and that provide capabilities for post-mission disposal. Other analysis tasks for assessing and limiting the risks of collisions are listed in AFI 91-202 and SMC Space Flight Worthiness Certification Criteria.

4. Debris Control Measures and Mitigation Options

Some operational procedures have already been adopted by various agencies to minimize debris generation. The first area in which debris-mitigation procedures have been incorporated is in mission operations, both for launch vehicles and for payloads. An example is upper stage modification for venting of unspent propellants and gases to prevent explosions due to the mixing of fuel residues. The disposal of spent rocket stages during flight has also been examined and in some cases altered for debris considerations. Launch planning is also affected by projections of the Collision Avoidance on Launch Program that warns of potential collisions or near misses with manned or man-capable vehicles. Some launches have been momentarily delayed during their countdowns to avoid flying in close proximity to orbiting objects. However, it should be noted that sensor limitations affect the accuracy of any predictions. In addition, the Computation of Miss Between Orbits (COMBO) Program projects proximity of payloads to debris objects soon after launch, and has been used on launches of manned missions.

Procedures affecting payloads include the use of the disposal orbit for satellites at the end of their functional lives. DoD, NOAA, INTELSAT, ESA, National Space Development Agency of Japan (NASDA), NASA and others have boosted aging GEO satellites to altitudes above geosynchronous orbits, attempting to reduce the probabilities of debris-producing collisions in GEO and freeing up valuable GEO orbital slots.

The second area in which debris-minimizing procedures have been adopted is the in-space testing associated with military programs. This testing is principally accomplished by means of mathematical modeling, but validation tests must be performed in space prior to development decisions. Experience from DoD space experiments involving the creation of orbital debris has proved that we can minimize the accumulation of debris by careful planning. The Delta 180 Space Defense Initiative test was planned in such a way that nearly all of the debris generated by these tests reentered within 6 months. This is because the test was conducted at low altitude to enhance orbital decay of the debris.

Predictions of the amount of debris and its orbital characteristics were made to assess range safety, debris orbit lifetimes, and potential interference with other space programs. The post-mission debris cloud was observed to verify predictions and to improve the breakup models. Such debris-minimizing test operations are now standard procedure, consistent with test requirements.

4.1 Mitigation Guidance

The following guidance for debris mitigation derives from the U.S. Government guidelines, which were adopted as requirements in the 2000 revision of the Air Force Instruction for mishap prevention, AFI 91-202. These requirements were used to develop the August 2000 draft of an SMC Debris Mitigation Requirements Document that was reviewed by SMC program offices. Comments from that review are reflected in the guidance below. Some key points from the review were that existing programs could be faced with expensive modifications if forced to comply with the mitigation requirements, launch vehicles could not support mandatory DoD requirements that could cause divergence in launch system design criteria from commercially provided services, and that required analysis and plans duplicate existing documentation such as a program's OSS&E Plan, the Accident Risk Assessment Report (ARAR) prepared for the spacecraft, the Missile System Prelaunch Safety Package (MSPSP) for the launch vehicle (the MSPSP typically incorporates the ARAR), and the Orbital Operations Handbook (OOH), which includes disposal plans and procedures. In partial response to these concerns, existing programs may request a waiver to the requirements such as was done for DMSP recently. FAA and FCC proposed rules are moving toward commercial system regulations consistent with DOD requirements, and mitigation plans may reference existing documents that support the requirements.

4.1.1 Programs and projects shall assess and limit the amount of debris released in a planned manner during normal operations. Program Offices shall document compliance as follows:

a) List all items/objects larger than 5 mm planned for release during deployment and operations. Estimate orbital lifetimes for these items/objects.
b) For objects larger than 5 mm that are released in a planned manner, a supporting analysis of the trade-off between cost of mitigation techniques (e.g., implementing bolt catchers, lens cap tethers), mission requirements, and risk shall be performed and documented. The risk to be determined is the probability that the ejected objects will collide with any operating spacecraft and cause it to lose its post-mission disposal capability.

Mitigation Options: *Compliance or noncompliance with the intent of the guidance must be documented, particularly for any debris larger than 5 mm in any dimension that remains on orbit for longer than 25 years.*

Launch vehicles and spacecraft can be designed so that they are litter-free; i.e., they dispose of separation devices, payload shrouds, and other expendable hardware (other than upper stage rocket bodies) at a low enough altitude and velocity that they do not become orbital. This is more difficult to do when two spacecraft share a common launch vehicle. In addition, stage-to-stage separation devices and spacecraft protective devices such as lens covers and other potential debris can be kept captive to the stage or spacecraft with lanyards or other provisions to minimize debris. This is being done in some cases as new build or new designs allow. These practices should be continued and expanded when possible.

The task of litter-free operations could combine design and operational practices to achieve the goal of limiting further orbital debris created by any space operations. As a result of these efforts, the growth rate of orbital debris will decline, although the overall debris population will still increase.

Research could be conducted to develop particle-free solid propellants. If successful, this technology research effort could eliminate the aluminum oxide (Al2O3) particulates produced by current solid rocket motor propellants. Such a program already exists for tactical missile propellant, but there is no work currently being performed for space applications.

4.1.2 Programs and projects shall assess and limit the probability of accidental explosion during and after completion of mission operations. Program Offices shall document compliance by identifying safety, mission assurance or other analysis results that demonstrate that the risk of an accidental explosion is less than 10^{-4} (1 in 10,000). Programs and projects shall perform and document an analysis of the risk of accidental explosion during or after completion of mission operations. If explosion risk is found to be unacceptably high relative to the program's tolerance for this risk, a supporting analysis of the trade-off between risk, mission requirements, and cost of risk reduction shall be performed and documented. If the program chooses not to implement mitigation to reduce explosion risk to an acceptable level, a second analysis shall include an assessment of risk posed to any operating spacecraft by debris resulting from an explosion. Program Offices shall also document compliance as follows:

a) A passivation plan for post-mission disposal shall be developed. This plan shall identify all passivation measures (e.g. spacecraft fuel depletion, propellant venting, disabling of battery charging systems, safing of bus and payloads) and any sources of stored energy that will remain.
b) Mission/cost assessments shall be identified that justify non-passivation of remaining sources of stored energy

Mitigation Options: *In developing the design of a spacecraft or upper stage, each program, via failure mode and effects analyses or equivalent analyses, should demonstrate either that there is no credible failure mode for accidental explosion, or, if such credible failure modes exist, design or operational procedures will limit the probability of the occurrence of such failure modes to no more than* 10^{-4}.

All on-board sources of stored energy of a spacecraft or upper stage should be depleted or safed when they are no longer required for mission operations or postmission disposal. Depletion should occur as soon as such an operation does not pose an unacceptable risk to the payload. Propellant depletion burns and compressed gas releases should be designed to minimize the probability of subsequent accidental collision and to minimize the impact of a subsequent accidental explosion. Note UPD10-39: para. 5.3.1, "Properly safing the bus and all payloads is a critical step in the disposal process… Safing the satellite takes precedence over all other disposal actions."

When stages and spacecraft do not have the capability to deorbit, they need to be made as inert as feasible. Expelling all propellants and pressurants and assuring that batteries are protected from spontaneous explosion require modifications in either design or operational practices for both stages and spacecraft. For systems that have multiburn (restart) capability, there are generally few, if any, design modifications required. For systems that do not have multiburn capability, design modifications to expel propellants are more extensive.

4.1.3 Program Offices shall assess and limit the probability that SMC space systems will become sources of debris due to collisions with man-made objects or micrometeoroids. Program Offices shall document compliance as follows:

a) An analysis of the risk of collision between mission spacecraft and cataloged objects during the mission time frame shall be performed and documented. This analysis shall consider not only collisions that produce large amounts of debris, but also collisions that will terminate a spacecraft's capability to perform post-mission disposal (for example, solar array and gravity gradient boom clipping), which are more likely than collisions that produce large amounts of debris. If the risk of loss of post-mission disposal capability is determined to be unacceptably high relative to the program's tolerance for this risk, a risk reduction analysis shall be performed and documented. This analysis shall address methods to reduce risk, e.g. mission orbit re-selection or operational collision avoidance. It shall include an analysis of the trade-off between cost, mission requirements, and risk reduction for each method. In addition, collision avoidance processes to be used during launch shall be identified.
b) An analysis of the risk of loss of spacecraft post-mission disposal capability due to impacts by untrackable debris or meteoroids during the mission time frame shall be performed and documented. If this risk is determined to be unacceptably high relative to the program's tolerance for this risk, a risk reduction analysis shall be performed and documented. This analysis shall address methods to reduce risk, e.g. shielding or location of critical spacecraft components. It shall include an analysis of the trade-off between cost, mission requirements, and risk reduction for each method.
c) For tether systems, requirements a) and b) apply to the tether for both intact and severed conditions.

Mitigation Options: *Assessment of the probability of collisions with known, cataloged objects should assist in determining the mission orbit. Additionally, the spacecraft vulnerability to collisions with small debris (less than a centimeter) should be assessed in terms of maintaining the capability for end-of-life disposal. Models of the small debris environment that are recommended for use are the NASA Engineering Model (Debris Assessment Software) and the ESA MASTER (Meteoroid and Space Debris Terrestrial Environment Reference) model. Example MASTER data from the ESA Space Debris Mitigation Handbook section on collision fluxes and impact risk assessment show that a spacecraft with 100 m^2 cross sectional area at 400 km altitude would have a mean time between impacts of debris objects greater than 1 cm of 885 years; the same size spacecraft at 780 km would have a mean time between impacts of 155 years. Equivalent data for debris greater than 1 mm are 3 years at 400 km and 1 year at 780 km. The NASA model is being updated with a new user interface, theoretical improvements and more*

recent measurements data; an earlier version is currently available through the NASA/JSC Website. Both the NASA and MASTER models are available through the Aerospace Corporation CORDS Office (Dr. Bill Ailor, 310-336-1135).

4.1.4 Programs and projects shall plan for, consistent with mission requirements, cost effective disposal procedures for launch vehicle components, upper stages, spacecraft, and other payloads at the end of mission life to minimize impact on future space operations. All SMC spacecraft shall be identified for disposal decisions, and the SMC Chief Engineer shall be notified when any of the following conditions occur:

a) The spacecraft has lost mission utility.

b) The nominal propellant level required for controlled deorbit or disposal maneuvers is projected to occur in six months.

c) Redundancy or other key functionality is lost in the end-of-life disposal or deorbit system.

4.1.5 Spacecraft disposal shall be accomplished by one of three methods:

a) Atmospheric reentry: Each spacecraft shall follow a plan for a controlled deorbit at the end of mission life. The orbital lifetime shall be no longer than 25 years after completion of mission, using conservative projections for solar activity, atmospheric drag and other perturbations. A controlled atmospheric reentry is the preferred method and non-selection of this method must be documented.

(1) If drag enhancement devices are planned to reduce the orbit lifetime, the Program Office shall demonstrate that such devices will significantly reduce the collision risk of the system or will not cause spacecraft or large debris to fragment if a collision occurs while the system is decaying from orbit.

(2) If a space structure will be disposed of by reentry into the Earth's atmosphere, the reentry casualty expectation shall be shown to be less than 10^{-4}.

b) Maneuvering to a storage orbit: Because of fuel gauging uncertainties near the end of mission, a program shall implement a maneuver strategy that reduces the risk of leaving the structure near an operational orbit regime. At end of life the structure may be relocated to one of the following storage regimes:

(1) LEO missions: Maneuver to an orbit with perigee altitude above 2000 km.

(2)MEO synchronous missions (4 hour, 6 hour, 12 hour orbits, etc.): Maneuver to an orbit with perigee altitude sufficiently above, or apogee altitude sufficiently below, the mission target altitude to limit collision probability in a manner consistent with mission requirements and cost. The collision risk assessment shall account for any eccentricity growth of the disposal orbit.

(3) Maneuver to an orbit with perigee altitude 300 km + 1000 $\times$ (average cross-sectional area in m^2/mass in kg) km above geosynchronous altitude.[7]

(4)Heliocentric, Earth-escape: Maneuver to remove the structure from Earth orbit, into a heliocentric orbit.

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[7] An alternative formulation for the supersynchronous disposal orbit has been adopted by the InterAgency Space Debris Coordination Committee (IADC), an international body of space agencies, with perigee given as 235 km + 1000 x C_R x A/M (area to mass ratio in m^2/kg), where C_R is the solar radiation pressure coefficient – typical values of 1 to 2. The IADC intent is to present this formula to the International Telecommunications Union for adoption as guidance to member states.

c) Direct retrieval: The structure shall be retrieved and removed from orbit as soon as practical after completion of mission.

4.1.6 Tether Systems shall be analyzed for both intact and severed conditions when performing trade-off s between alternative disposal strategies.

4.1.7 Program Offices shall document compliance as follows:

a) Identify the disposal option planned for each spacecraft.
b) Identify the estimated timeframe for disposal and the decision processes associated with the disposal decision.

Mitigation Options: *Requirement (a) as given in AFI 91-202 states that the orbital lifetime of a spacecraft shall be no longer than 25 years after completion of mission using conservative projections for solar activity, atmospheric drag, and other perturbations. The requirement of a 25-year lifetime is an indirect means of performing debris mitigation and may not be either an accurate or cost effective metric. The value of 25 years is currently under study by the IADC Working Group for Debris Mitigation for the development of international guidelines. The 25-year limit was originally selected by NASA as a compromise from requiring immediate deorbit at end of mission and the attendant high cost in terms of propellant for the deorbit. While little change in overall collision risks is shown in projections using 25- and 50-year deorbit requirements, NASA selected the 25-year limit based on estimates that deorbit 25 years after end of mission would only require 10% of a typical spacecraft's mission propellant budget.*

A spectrum of orbits with different eccentricities will decay in 25 years, but the level of collision risk may vary throughout that spectrum. Some decay orbits may have collision risk concentrated during the later years at lower altitudes where the contributions of collisions to the debris environment are shorter lived. In addition, the requirement to use conservative projections for solar activity, atmospheric drag, and other perturbations, rather than average projections, will increase the cost of disposal by placing more severe requirements on propellant budgets or drag enhancement devices. To circumvent these limitations, it was recommended by SMC reviewers that collision risk be used as a metric rather than a 25-year lifetime since it is more direct and can be subject to trading with cost and mission requirements. However, the 25-year lifetime was retained in this revision of the handbook to maintain commonality with NASA and U.S. Government guidelines pending the IADC resolution of the lifetime limit for international guidelines. Program Offices are encouraged to conduct the alternative analysis suggested above if contemplating the use of a 25-year orbit for disposal – comparing the collision risk over time of the 25-year orbit to that of alternative orbits as well as the direct deorbit option.

Planning for end-of-life disposal is best done in the early design phases both to be cost effective and to assure that adequate system capabilities will be available for the disposal phase. Disposal or deorbiting of spent upper stages or spacecraft is a more aggressive and effective strategy than merely inerting spent stages and spacecraft, since it removes from the environment significant mass that could become future debris.

For new spacecraft and launch systems, there are a large number of trade-off s as to the physical and functional interface between the stage and spacecraft that can minimize the adverse effect of implementing a disposal requirement. Studies are required to assess the cost effectiveness of these trade-off s, given a particular system and mission.

For near-term concerns, the highest priority for disposal must be given to high-use altitudes. However, disposal of debris at these altitudes is most costly and difficult. Two types of approaches might be explored: mission design and system configuration and operations. Each needs to be applied to both LEO and GEO systems. Studies are required to assess the cost effectiveness of these options given a particular system and mission.

Some debris can be disposed of by careful mission design, but this may sometimes result in a significant performance penalty to both spacecraft and launch systems.

For some missions, the performance of the launch vehicle has sufficient margin that the stage has propellant available to do a deorbit burn. The stage needs to be modified to provide the mission life and guidance and control capabilities needed to do a controlled deorbit.

When the mission requires delivery of a spacecraft which itself has a maneuver capability, two alternatives are possible. One is to leave the upper stage attached for delivery of the spacecraft to orbit to maximize its maneuver capability. The second is to separate the spacecraft at sub-orbital velocity so that the stage decays naturally and the spacecraft uses its onboard propulsion to establish its orbit. From a cost-penalty perspective, the first alternative results in a greater mass in orbit, a potential debris hazard, while the second alternative increases the complexity of the spacecraft. Assessing which alternative is more appropriate requires further study.

An alternative to reentry and ocean disposal is relocation to a "trash" orbit. In LEO, this is not an advantageous strategy because it generally requires a two-burn maneuver that is more costly in terms of fuel than the single burn that is required for entry. During the 1980's and early 1990's, the Soviet Union used a trash orbit in LEO to dispose of 31 of their nuclear power sources.

Another alternative to a controlled direct reentry is a maneuver that lowers the perigee such that the inertial orbital lifetime is constrained to a period such as 25 years. Such a maneuver removes the object from the region of high hazard quickly and removes the mass and cross section from orbit in a small fraction of the orbital lifetime without such a maneuver. This is significantly less costly than a targeted entry. It makes the eventual reentry happen earlier, but raises questions regarding liability issues.

For GEO missions, the pertinent considerations for disposal are the launch date, launch azimuth, and the perigee of the transfer stage. For multiburn systems, positive ocean disposal can be achieved with an apogee burn of a few meters/second if the stage has sufficient battery lifetime and contains an attitude reference and control system.

In addition, there is a set of launch times to GEO that so align the orbit of the transfer stage that natural forces, e.g., Sun, Moon, Earth properties etc., act to lower or raise the perigee of the stage. Consideration of the effect of these forces can minimize the cost of active control of liquid propellant stages and is a low-cost technique for the disposal of solid rocket motor stages. The only alternative strategy for the disposal of solid rocket motors is to orient the thrust vector of the rocket in a direction so that the perigee of the transfer orbit resulting from the burn is at a low enough altitude to cause the stage eventually to reenter (sometimes referred to as an off-axis burn). This strategy results in about l5% performance penalty for the stage.

Use of disposal orbits is a technically feasible strategy for clearing the geostationary orbit region, but is not the only available strategy. The cost effectiveness of a disposal orbit strategy compared with other strategies has not been examined. If raising the orbit is to be the technique of choice, then it requires planning and reserving the necessary propellant resources to effect the maneuver. Preliminary studies indicate that the orbit needs to be raised on the order of 300 km to serve the intended purpose, not the 40 to 70 km that has been used by some operators. The performance cost to reboost is 3.64 m/s for each 100 km or 1.69 kg of propellant for each 1000 kg of spacecraft mass. To reboost 300 km is comparable to 3 months stationkeeping.

Mission design appears to be the least-cost option for disposal. However, systems not designed with a disposal requirement have other alternatives available, such as design modifications to current systems or design attributes for new systems.

For LEO stages or spacecraft, it may be feasible to maneuver to lower the perigee and employ some device to significantly increase drag. In geosynchronous transfer stages, the design and operation timeline could be modified so that the separation and avoidance maneuver could provide the velocity increment to cause the stage to enter.

Removal is the elimination of space objects by another system. The following discussion pertains only to LEO because at present there is no capability or perceived need for a removal system at GEO. Removal options may also raise significant international legal issues.

The removal of large, inert objects requires an active maneuver vehicle with the capability to rendezvous with and grapple an inert, tumbling, and non-cooperative target and the ability to apply properly and accurately the required velocity increment to move the object to a desired orbit. These capabilities have been demonstrated by the Space Shuttle, but no unmanned system has these capabilities for higher altitudes and inclinations.

The design, development, and operation of a maneuverable stage to remove other stages and spacecraft requires a high degree of automation in rendezvous, grapple, and entry burn management if operations costs are to be kept reasonable. The long- and short-range systems to acquire, assess the orientation, grapple, secure, determine the center of mass, and plan the duration and timing of the entry burn all require development and demonstration of both capability and cost effectiveness. The component technologies require study and analysis, followed by breadboard and prototype development.

4.2 Orbital Stability Considerations for Disposal Orbits

The Office of Development Plans (SMC/XR) sponsored three studies of the end-of-life disposal guidelines published by NASA in 1995.[8] The first study encompassed disposal orbit stability and strategy for GEO.[9] The second study was for atmospheric reentry,[10] and the third for disposal orbit stability and direct reentry strategy for orbits below GEO and above LEO.[11]

GEO Disposal. In order to understand the long-term orbit perturbations and stability of super-synchronous orbits at 250 to 350 km above synchronous altitude, analysis and numerical integration techniques were employed to study eccentricity variations. Perturbations included sun/moon gravitational attractions and solar radiation pressure. Both the analytic and numerical techniques showed that the long-term eccentricity variations are well behaved (sinusoidal) with no secular change. The amplitude of the sinusoidal variation was found to be proportional to initial eccentricity and to have some dependence on initial argument of perigee. Very long-term (10 to 11 years) eccentricity variations resulted from sun/moon attractions, and the amplitude of annual variations due to solar radiation pressure depended on spacecraft area to mass ratio. Recommendations for GEO disposal strategy were to raise the mean orbit altitude by 350 km with initial eccentricity less than 0.001. For spacecraft with large area to mass ratios, additional altitude is needed to compensate for eccentricity variations due to solar radiation pressure. A reserve ΔV budget of 13 m/sec for disposal maneuvers was cited. This strategy will keep the disposed GEO debris at least 300 km above geosynchronous altitude to allow adequate clearance for longitude changes of operational GEO spacecraft. An Aerospace Corporation study (to be completed in February

[8] *Guidelines and Assessment Procedures for Limiting Orbital Debris*, NASA Safety Standard 1740.14, Office of Safety and Mission Assurance, August 1995.
[9] Chao, C. C., "Geosynchronous Disposal Orbit Stability," Technical Report TOR-97(1106)-7, The Aerospace Corporation, September 1997.
[10] Meyer, K. W. and Chao, C. C., "Atmospheric Reentry Disposal for Low-Altitude Spacecraft," Journal of Spacecraft and Rockets, Vol. 37, No. 5, September-October 2000.
[11] Chao, C. C., "MEO Disposal Orbit Stability and Direct Reentry Strategy," AAS Paper No. 00-152, AAS/AIAA Space Flight Mechanics Meeting, January 23-26, 2000, Clearwater, FL.

2002) is investigating the long-term stability of subsynchronous GTO disposal orbits in order to provide guidance for protecting the longitudinal transfer region for GEO spacecraft.

Atmospheric Reentry. Atmospheric reentry was analyzed under four different options for bringing spacecraft in within 25 years of end of mission: 1) chemical propulsion maneuvers, 2) low-thrust propulsion transfer, 3) balloon (drag enhancement device) deployment, and 4) the combination of chemical propulsion and balloon deployment. Spacecraft of various ballistic coefficient values and orbital altitudes of up to 2000 km were studied to determine the required fuel or drag enhancement device needed for deorbit within 25 years; using realistic values for specific impulse Isp and balloon material density, the additional weight required for deorbit was found. The risk of collisions with other space objects during the 25-year reentry was also addressed. The program LIFETIME[12] was used to establish that the disposal orbits led to reentry within 25 years; initial and disposal orbits were all taken as circular. Epoch for start of the 25-year orbit was 1 January 2000. Spacecraft dry mass of 1000 kg was assumed, excluding propellant or balloon. The spacecraft drag coefficient was taken as 2.2. Table 4-1 gives representative ballistic coefficients and maximum initial altitudes for reentry within 25 years without disposal efforts.

Table 4-1. Maximum initial altitude values that ensure a 25-year orbital lifetime

Ballistic coefficient, m^2/kg	Maximum initial altitude, km
0.01	640
0.02	696
0.04	756
0.08	820

The evaluation of the four options for disposal found that low-thrust transfers (I_{sp} = 3000 sec) required about a tenth of the additional fuel of chemical propulsion (I_{sp} = 300 sec) for deorbit within 25 years. For example, from an initial altitude of 1400 km, the additional fuel for deorbit of a spacecraft with ballistic coefficient of 0.08 m^2/kg was about 10 kg for low-thrust maneuvering while the chemical propulsion system required 100 kg of additional fuel. Additional deorbit weight for balloon deployment, assuming a balloon material density of 0.132 kg/m^2 and neglecting the mass of the balloon deployment device, was found to be roughly quadratic with initial altitude. Balloon deployment was studied only for initial orbit altitudes up to 1000 km since the size and mass of the balloon becomes too large for practical applications at higher altitudes. Typical balloon weights for deorbit of spacecraft with ballistic coefficient of 0.08 m^2/kg were 5 kg for 850 km initial altitude and 85 kg for 1000 km. The option combining chemical propulsion with balloon deployment uses an approach with chemical maneuvers to reduce the initial altitude to 800 km (the altitude with the largest weight savings for the balloon option in comparison to the chemical propulsion option) followed by balloon deployment. Weight savings (relative to chemical propulsion alone) of about 20 kg over the altitude range of 800 to 2000 km were found for spacecraft of ballistic coefficient 0.01 m^2/kg while weight savings were minimal for spacecraft of ballistic coefficient of 0.08 m^2/kg.

[12] Chao, C. C., and Platt, M. H., "An Accurate and Efficient Tool for Orbit Lifetime Predictions," AAS/AIAA Paper 91-134, February 1991.

Collision risks during the 25-year reentry orbit were also assessed for the four options. The U.S. Space Command catalog of 14 January 1998 was used with an assumed uniform growth rate of 250 satellites per year. The risk was found to be small for most of the deorbit options, on the order of 1 collision per 1000 deorbit events; however, the largest balloon deployed (from an initial altitude of 1000 km) had a collision rate of about 1 collision per 50 deorbits. Smaller debris impacts over 25 years led to the recommendation that for the balloon option to be feasible, the balloon material should be designed to survive an impact with a 1 mm diameter particle.

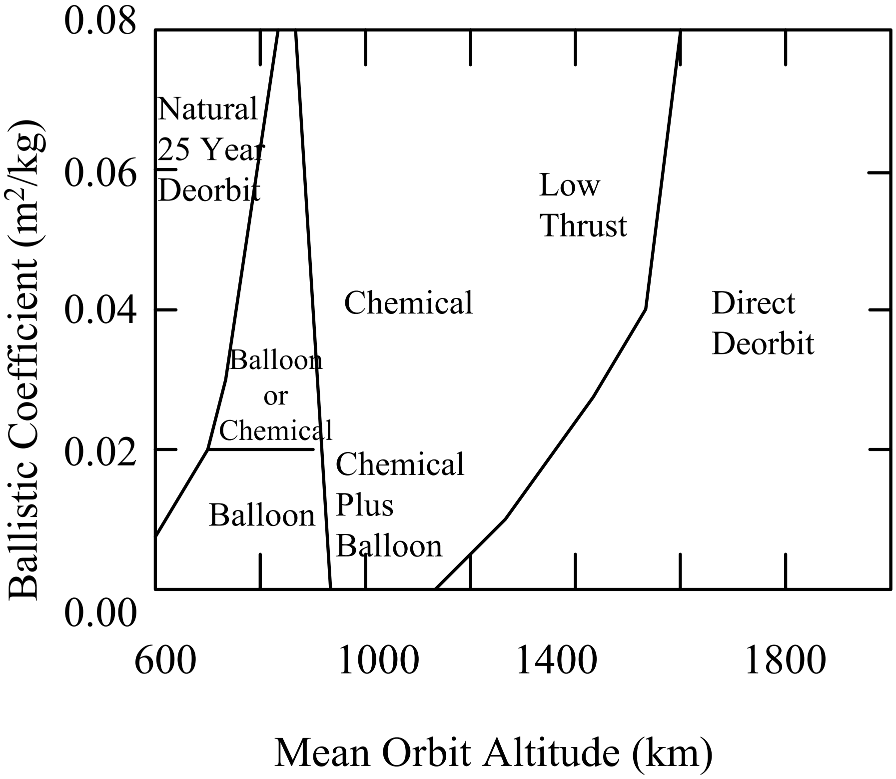

Fig. 4-1. Regions where explored disposal methods were the most weight efficient.

Figure 4-1 shows the general trends and conclusions from the study of disposal options. The boundaries separating the different disposal methods are notional in that costs and spacecraft operational capabilities for reentry must be considered for each mission. The low-thrust option offers significant reduction in additional weight, and as indicated in Fig. 4-1, may be the only viable option for high initial altitudes and large ballistic coefficients. However, low-thrust transfer occurs over much longer times than chemical transfer and requires an operational attitude control system during the entire transfer. At the highest altitudes, a direct deorbit (within half an orbital period) is more mass efficient than transfer to a circular orbit with a 25-year lifetime. At the lowest altitudes, the 25-year lifetime is satisfied without need for further action.

MEO Disposal. The study of MEO disposal addressed the orbit stability of two regions, one between 2000 and 4000 km as a potential storage region for missions at high LEO or low MEO and the other as storage zones for GPS, Molniya satellites and geosynchronous transfer orbit (GTO) stages. Long-term variations in semi-major axis and eccentricity were examined through analytical expansions and approximations. Then numerical and semi-analytic orbit propagators were used to study the disposal orbits for up to 200 years. While possible solar radiation induced

resonances were noted for disposal orbits at 2500 and 3000 km, orbits selected to avoid resonances were stable. Long-term (100-year) numerical integration to determine proper orbit selection (altitude and inclination not close to one of the resonance conditions) is recommended, particularly for spacecraft with large solar panels. For LEO missions with mean orbit altitude less than 1500 km, direct reentry or deorbit within 25 years is recommended. For missions with mean altitude greater than 1500 km, the recommendation is for disposal in an orbit with minimum perigee of 2500 km. Investigation of GPS disposal orbits above SSO used a doubly averaged equation in eccentricity that revealed a term in the expansion leading to large growth in eccentricity. The term is the sine of an angle of twice the argument of perigee plus right ascension of the ascending node ($2\omega + \Omega$). For initial eccentricity of the disposal orbit of 0.02 and the angle term equal to 270 degrees, eccentricity grew to 0.5 in 140 years. Recommendations for GPS disposal were that the orbit should be raised by at least 500 km with eccentricity no greater than 0.005 and initial argument of perigee inside the windows determined for each of the six GPS planes[13]. Estimated ΔV is 50 to 70 m/sec.

During review of the SMC Debris Mitigation Requirements Document, the GPS Program Office noted that recommendations for the LEO-MEO and MEO-GEO disposal regions extend to 500 km below and 500 km above semi-synchronous altitude, respectively. However, these regions overlap with both the current and future GPS operational constellation shell. In addition, disposal orbits in those regions near semi-synchronous altitude can undergo large eccentricity growth and cross back into the GPS operational shell. As a result, the portions of this guideline pertaining to GPS are deficient, and specific altitude boundaries near GPS should be removed from the guideline. Work is currently underway to develop a pertinent disposal procedure for GPS. After GPS has approved this procedure, it may be reflected in a modification to the guidelines. Orbital systems of other users of the semi-synchronous altitude region (e.g., GLONASS or the proposed Galileo constellation) should also be part of disposal orbit considerations to ensure noninterference with their operations.

Molniya disposal orbits demonstrated long-period eccentricity variations with large amplitude. To preserve a minimum perigee of 2000 km, the initial perigee of the disposal orbit should be raised to 3000 km. The apogee of a Molniya disposal orbit need not be lowered to 500 km below GEO since the inactive satellite will not come close to the geosynchronous region due to its high declination near apogee if the argument of perigee remains close to 270 degrees. GTO disposal orbits (perigee 2500 km, apogee 35,000 km, inclination 28.5 degrees) were found to be very stable with no large variations in eccentricity and inclination.

Direct reentry was also investigated under a strategy of performing single or multiple burns to ensure a controlled reentry with impact in a broad ocean area.

Figure 4-2 shows the ΔV requirements for single-burn direct reentry and transfer to a 2500 km disposal orbit.

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[13] Gick, R. A., and Chao, C. C., "GPS Disposal Orbit Stability and Sensitivity Study," AAS Paper 01-244, AAS/AIAA Space Flight Mechanics Meeting, Santa Barbara, CA, February 11-15, 2001.

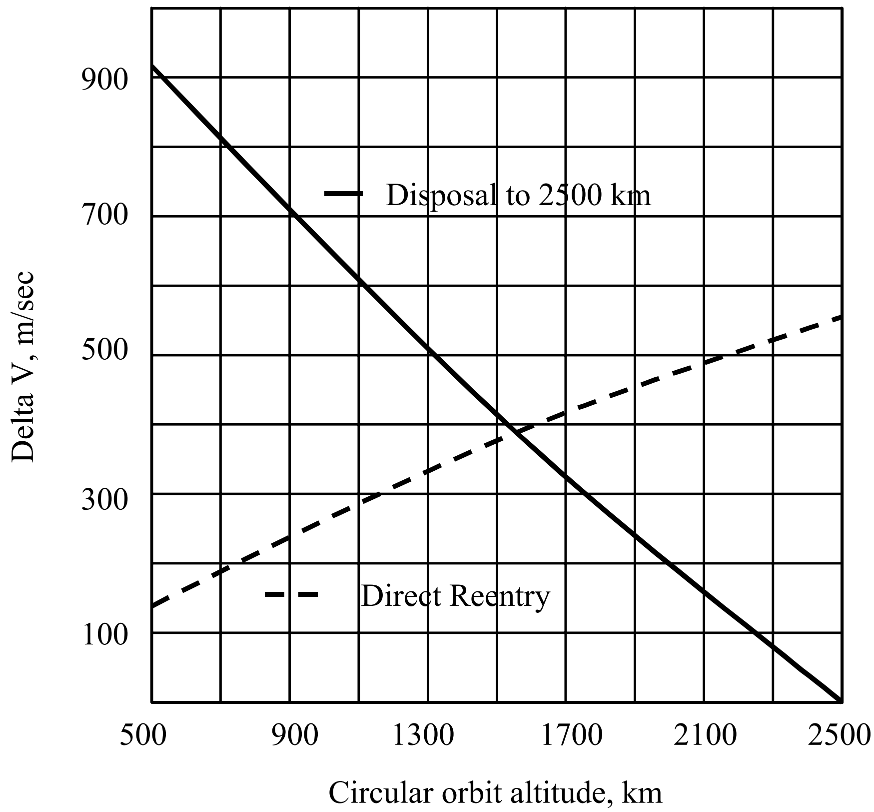

Fig. 4-2. Delta V requirements for direct reentry and disposal.

For Molniya satellites, direct reentry requires less ΔV than placement in a disposal orbit if EOL eccentricity is greater than 0.7. Direct reentry for eccentricity of 0.72 would require a ΔV of about 95 m/sec compared to just over 160 m/sec for disposal. For a typical GTO, direct reentry requires about 40 m/sec but 200 m/sec to place the stage in a disposal orbit. Other than potential ΔV savings, direct reentry options for Molniya and GTO objects should be favored over disposal orbits due to the relatively high population density near the two inclinations, 28.5 and 63.4 degrees, and the collision hazards these highly elliptical orbits pose to SSO missions as well as their own active and disposal orbits.

Summary[14]. U.S. Government standard practices as adopted in DoD and AF instructions for debris mitigation are generally supported by the analysis described here but should be reviewed to account for orbital variations in identified disposal regions. For GEO disposal, the standard practice's reference to only an initial perigee altitude above synchronous altitude does not acknowledge eccentricity variations or the influence of spacecraft area to mass ratio. Both the NASA guidelines and those under development by the Inter-Agency Space Debris Coordination (IADC) Committee explicitly include spacecraft area-to-mass ratio as a factor for increasing perigee of the disposal orbit. The IADC guideline for disposal altitude change is 235 km plus a factor of 1000 times the spacecraft reflectivity coefficient times the area to mass ratio. The need to minimize initial eccentricity should also be introduced into the U.S. Government practices, as well as DoD, NASA, and international guidelines.

[14] Campbell, S., C.C. Chao, R.A. Gick, M. Sorge, "Orbital Stability and Other Considerations for U.S. Government Guidelines on Post-Mission Disposal of Space Structures," Third European Conference on Space Debris, ESOC, Darmstadt, Germany, 19-21 March 2001.

Atmospheric reentry standard practices appear feasible based on the study of a range of options. Chemical propulsion has wider applicability due to the more frequent availability of on-board thrusters. The additional wet mass for chemical propulsion deorbit may be 10 to 20% or more of the spacecraft dry mass. While wet mass is not as strong a cost driver as dry mass, cost may be the determining factor in selecting a disposal method. Simplicity, reliability and launch vehicle weight margin are other factors that could drive the selection. Low-thrust transfers offer significant reductions in deorbit mass but require the spacecraft attitude control system to be operational long after end of mission. Balloons or other drag enhancement devices can provide weight savings over chemical maneuvers and should be relatively simple to implement, but do present a larger cross-sectional area for collisions and impacts from smaller debris. There has been little operational experience with balloon systems so the simplicity of this option may be overestimated. Combining chemical maneuvers with a balloon can result in weight savings, but at the cost of increased complexity.

The risk of human casualties from atmospheric reentries is to be limited to less than 1 in 10,000 for each reentry. The casualty exposure is directly related to the inclination of the orbiting object in that a random reentry can occur anywhere within the North and South latitudes equal to the inclination value. An effect of requiring reentry within 25 years of end-of-mission is that the number and rate of reentries will increase, and casualty exposure will also increase relative to the "do-nothing" case of simply abandoning spacecraft on orbit at end of mission.

The direct reentry technique provides controlled disposal, typically into an ocean area, with ΔV savings for lower LEO spacecraft, Molniya satellites and GTO stages. However, application of the technique requires accurate tracking of spacecraft to support calculations for designing the retro-burn, to maintain collision avoidance assurance for manned space systems, and intensive analysis of break-up and debris impact footprints. Effective employment of the direct reentry technique also requires good ground station coverage during apogee burns. Thus, this technique may not be universally applicable.

MEO disposal orbits, including those near 2000 to 2500 km, should be selected to avoid resonance regions. A general recommendation is that the initial eccentricity of the disposal orbit be limited to nearly circular. Further recommendations await GPS approval of spacecraft disposal procedures.

5. Conclusions

In 1995, SMC organizations were surveyed to determine the degree of compliance with National and DoD debris policies. The survey was developed by the AF Research Laboratory (Phillips Laboratory) at the direction of the Secretary of the Air Force Office of Space Policy (SAF/SX). The principal results of the survey were that debris control measures were in place to limit release of operational debris (except for lens cap releases on some older systems), avoid explosions, and conduct post mission disposal actions in concert with AFSPC. However, debris hazards and mitigation measures were not subjects of design reviews. The survey was repeated in 1999 to support efforts of the InterAgency Debris Coordination Committee (IADC) in harmonizing international debris mitigation practices. The results showed an increased awareness of debris issues, and inclusion of debris management in program design reviews and in reviews with AFSPC. Other survey responses cited the utility of the Contamination and Collision Avoidance Maneuver (CCAM) in minimizing the risk of collisions as well as maneuvers performed to minimize the risk of meteorite impacts during the Leonid meteor showers. A part of the increased awareness is likely due to the U.S. Government Guidelines on standard practices for debris mitigation having been adopted as requirements in the revision to AFI 91-202 and reflected in Space Flight Worthiness Criteria. However, further determination of the validity of the 25-year limit for deorbit after end of mission and requirements for disposal orbits that fully consider the stability of such orbits is needed.

Debris control measures to limit or eliminate operational debris, accidental explosions, and collisions with cataloged objects are readily implemented and cost-effective. However, insuring that spacecraft control can be maintained after collisions with smaller debris can be quite costly in terms of design and implementation. In addition, the contract scope of future space programs does not appear to support the massive shielding and structural design needed to fully protect the spacecraft from debris impact. The debris mitigation survey responses reflect the general feeling that total protection from debris and meteoroid impact would add enormous cost, and the redesign of currently manufactured spacecraft in order to reduce debris effects would also involve prohibitive costs. Post-mission disposal of spacecraft and upper stages can also be costly or impractical, particularly if such considerations are not included in the early design and mission planning stages.

The effects of man-made orbital debris, chemical fuel releases, outgassing products, and naturally occurring meteoroids has relatively low visibility for analysts addressing the lifetime of current and future spacecraft. However, the reason for this does not lie in a lack of general concern, but rather, in a lack of reliable, quantitative models to address the issue. Only rudimentary models to address the effects of outgassing and chemical self-contamination are widely used. Several important space experiments have contributed data that can help estimate possible impacts. Those space experiments appear to show that spacecraft self-contamination is the largest threat.

6. References

6.1 Government Documents

a) Interagency Report on Orbital Debris 1995
b) DoD Space Policy, No. 3100.10, 9 Jul 99
c) NASA Safety Standard 1740.14, Guidelines and Assessment Procedures for Limiting Orbital Debris
d) "Illumination of Objects in Space by Lasers", DoDI 3100.11, Department of Defense Instruction, Memorandum for Commander in Chief, U.S. Space Command, Money, Arthur L., Assistant Secretary of Defense, Command and Control, Communications, and Intelligence, Washington, DC 20301, 31 March 2000.
e) National Reconnaissance Office Satellite Debris Mitigation – Design Guidelines, NROI 82-2, 6 Jan 99
f) National Reconnaissance Office Satellite Debris Mitigation – End of Life, NROI 82-3, 6 Jan 99
g) National Reconnaissance Office Satellite Debris Mitigation Policy, NROI 82-6, 6 Jan 99
h) Satellite Disposal Procedures, UPD10-39, 3 Nov 97
i) USG Orbital Debris Mitigation Guidelines, Dec 97
j) AFI 91-202, The U.S. Air Force Mishap Prevention Program, Safety, Chapter 11 Space Safety, 1 Aug 98, and draft revision in 2002.
k) EWR 127-1, Range Safety
l) Space Support DoDI 3100.12, 14 Sep 00

6.2 Non-Government Documents

a) ESA Debris Mitigation Handbook, 30 Oct 98

Appendix A – Hazards Catalog

Volume I – Collision Hazards

1. Introduction

Collisions are of major concern for several reasons. First, they can cause termination of satellite function mission. The resulting cost in terms of replacement of the lost asset and loss of military capability can be high. Second, the resulting loss of controllability can lead to additional hazards, such as ground risk posed by a damaged launch vehicle, or collision risk posed to other operating satellites by a damaged primary satellite or loss of a controlled reentry capability. Third, orbital collisions between trackable objects can, depending on the impact geometry, result in the generation of large amounts of secondary debris, thereby increasing the background debris environment.

Collision hazards include all types of unplanned encounters with aircraft, birds, ice crystals, raindrops, other satellites, orbital debris, and meteoroids. However, collision hazards of most direct concern to SMC are those between (1) a spacecraft and another related or unrelated spacecraft, (2) a spacecraft and objects deployed with or from it, (3) a spacecraft and orbiting space debris, or (4) a reentering spacecraft (or its debris) and people and property on the ground. These are the hazards that SMC has the greatest responsibility to avoid or minimize through careful analysis and planning. Collision hazards are discussed in five separate sub-categories as follows:

1. Launch and recovery area hazards to the spacecraft;
2. Avoiding collisions with known satellites during launch;
3. Hazards to the spacecraft from orbital debris and meteoroids (includes steps to limit creation of debris);
4. On-orbit maneuver collision hazards;
5. Hazards to ships, aircraft, people, and property as a result of reentering objects, including debris.

The level of SMC responsibility depends on the type of collision hazard. Traditional system-safety procedures vigorously support design efforts to overcome the collision hazards in 1, 2, 3, and 5 above. Launch and recovery ranges have major responsibility for 1; and SMC has major responsibility for 2, 3, 4, and 5. To illustrate these relationships, all collision hazards are discussed; but more emphasis is placed on those for which SMC has direct responsibility.

2. Launch and Recovery Area Hazards to the Spacecraft

Usually a launch range, such as the Eastern Range (ER) or the Western Range (WR) will be responsible for all safety until the spacecraft achieves orbit, or it passes a designated turnover point. SMC is most concerned with the collision hazards present on orbit and during reentry. However, a spacecraft damaged even slightly during launch can be of great danger to people and property on-orbit or during reentry. Therefore, a full safety hazard analysis should include risk factors associated with the launch-phase mishaps.

Launch safety consists of three major areas:

1) Range Safety – All launch operations conducted from a Major Range Test Facility Base (MRTFB) will comply with DoDD 3200.11, MRTFB Range Safety Requirements. Range safety personnel at recovery areas such as Kwajalein have well-established procedures for minimizing collision hazards during splashdown or recovery. For the most part, the procedures involve clearing the operations area of aircraft and/or ships, monitoring the flight of large birds, and

watching for clouds that may contain harmful precipitation. SMC generally has little responsibility for this phase of a mission.

2) Launch Collision Avoidance – Operators take appropriate actions to minimize the risk of collisions with other satellites or space debris from launch until spacecraft achieves orbit, or it passes a designated turnover point (i.e., Range Safety and Mission Assurance Conjunction Analysis). Collision with launch area objects such as aircraft, birds, ice, and raindrops during both launch and recovery operations are major concerns to satellite designers, mission planners, and safety personnel. Risk mitigation steps are taken to keep aircraft away; however, bird strikes and weather hazards in the launch or recovery area are considered in the design of the vehicles/spacecraft.
3) Mission Flight Control – Space launch operators have adequate measures in place to ensure complete control over launch vehicles at all times so that the surrounding public will not be exposed to undue risk.

2.1 Design Considerations

Extra weight is extremely costly to space programs; therefore, boosters, nose cones, spacecraft, and reentry vehicles must be designed to be as light as possible. Launch-area collision hazards and their physical effects must also be well understood and quantified to allow design of the lightest possible structures and shielding, or to determine the minimum number of redundant circuits/sub-systems to ensure an acceptably low probability of mission failure if a collision were to occur.

Designing a spacecraft to withstand launch and recovery area hazards is the direct concern of system or test program offices. In addition, Service procurement and development agencies are directly involved through the guidance and standards they impose. Air Force system program offices (SPOs), for example, report to Air Force Space Command (AFSPC) through the Space and Missile Systems Center (SMC). Air Force SPOs are directly responsible for the design of all Air Force vehicles (stages), nose cones, protective shrouds, etc., which must penetrate the atmosphere during launch or recovery. Additionally, hazards are the concern of SMC System Quality organizations such as Specialty Engineering and Product Assurance (SMC/AX) and Space Test and Experimentation (SMC/TE) as reflected in the standards they prepare and recommend to the vehicle SPOs. Finally, launch or recovery hazards, as well as others, are of concern to the Directorate of Safety (SMC/SE) as reflected in their policies and the oversight function they perform for the SPO system-safety programs. The other Services have similar engineering, safety, and quality assurance organizations that specify design and testing standards for launch vehicles.

2.2 Operational Steps to Minimize Risk

Launch and recovery ranges maintain extensive aerial and sea surveillance networks to ensure that aircraft and surface vessels remain outside their respective restricted areas. An Air Weather Service detachment keeps a close vigil on approaching clouds that might precipitate water droplets or discharge static electricity as the launch vehicle passes through the atmosphere. Surveillance includes helicopters and local range radars. During night launches, fixed-wing aircraft patrol further out from the launch complex. Instrumented range support platforms may be located near the launch site or other locations downrange to collect telemetry data or observe reentering objects jettisoned during launch and boost as well as to watch for intruding ships or aircraft. All are in continuous communication with Launch Control and Range Safety. Launch trajectories that minimize the amount of time within the troposphere, where most of the weather is contained, reduce effects of wind and precipitation (rain, sleet, or hail) and chance of bird strikes.

2.3 Assessment Tools

A large array of assessment tools exists for evaluating close approaches between launching vehicles and resident space objects (RSO), e.g., COMBO, CALIPER, COLLISION VISION, STK CAT, etc. The large majority of these tools provide miss distances between objects, which is sufficient in some cases for launch collision avoidance. In other cases, more fidelity in modeling collision risk is necessary to avoid launch window closure due to excessive conservatism. In these cases, it is necessary to use an assessment tool that also includes an estimate of positional uncertainty (from covariance or empirical analyses) about both objects. Using such information, the analysis can produce not only miss distances, but actual probabilities of collision, as well. This additional information allows launch directors to trade between launch delay and mission risk based on an accurate probabilistic evaluation of any predicted collisions. In general, launch window closures due to conjunctions with manned or man-able space objects are dictated by separate Range Safety constraints.

In all cases, the accuracy of the data provided to the assessment tool is critical in determining the fidelity of the derived result. A commonly available set of positional locations for RSO is the General Perturbations catalog maintained by the Space Surveillance Network (SSN). This set of orbital elements, in two-line format, allows the prediction of RSO locations using fast analytic techniques. Accuracy of this type of data is generally sufficient only as an indicator of potential conjunctions, not as a means of determining an avoidance strategy. A higher level of accuracy is obtainable by using the numerically integrated Special Perturbations (SP) predictions based on SSN data. This type of data is the best available for most of the debris objects in near-Earth orbit. Even more accurate than this data type is the predicted High Precision (HP) ephemeris maintained by spacecraft operators, which includes predicted maneuvers. Combinations of SP and HP data provide sufficient accuracy upon which to base avoidance maneuver or launch delay decisions.

3. Avoiding Collisions with Tracked Objects during Launch

Responsibility for avoiding a collision or close encounters during launch with a spacecraft already on-orbit is shared by launch-control agencies, SPOs, and agencies that control on-orbit spacecraft such as NASA and AF Space Command. An essential part of avoiding collisions is knowing where the on-orbit satellites are at any time, which is more complex than generally recognized for the following reasons: 1) U.S. Space Command (USSPACECOM) presently maintains a catalog of more than 9000 objects in space, the locations of which are not static and are not known with sufficient accuracy to ensure safety; 2) the actual trajectory of a spacecraft during launch and early orbit maneuvers can vary within Range Safety established limits from the planned nominal trajectory; 3) the positional accuracy available from ground-based sensors may not be sufficient to ensure adequate separation between satellites at some crowded Geosynchronous Equatorial Orbit (GEO) stations; and 4) there is no definition of what is an acceptable approach distance. However, criteria for close approaches of the Shuttle or ISS to known objects, including debris, have been established as a result of the Challenger accident. A 5x25x5 km alert box is used for screening during the entire mission. For objects that enter the alert box a reassessment is done using a more intense "special perturbations" algorithm to determine if it is in the 2x2x5 km maneuver box. If it is in this box, recommendations will be given to maneuver out of the way.

An in-depth study was initiated by USSPACECOM to quantify the element set accuracies and a collision probability and risk analysis study was initiated by the Johnson Space Center Operations Group. The study resulted in the following criteria:

a) If during pre-launch, a potential collision is identified (i.e., a threat object will pass inside a keepout box of specified size centered on the Shuttle) any time during the first four hours of a nominal mission, then the launch will be delayed one minute to ensure clearance.

b) If a collision (within similar approach criteria) is identified during on-orbit operations, then an avoidance maneuver will be initiated if the maneuver does not compromise either primary payload or mission objectives.

Tracking objects in space is a responsibility of U.S. Space Command's SSN, a network of DoD radars and optical tracking facilities, and the command's SPADOC, which collects and catalogs the data collected by the network. SPADOC maintains a computerized database of known objects in space (currently over 9000) called the Space Object Catalog. The great majority of these catalogued objects are low Earth orbiting objects and are approximately 10 cm apparent radar cross section or larger. Due to sensor characteristics, the size of the smallest detectable objects increases with altitude. The largest percentages of tracked objects are debris. Only 5% of the cataloged objects in Earth orbit represent operational spacecraft.

3.1 Design Considerations

To ensure that launch and early-orbit maneuvers will not conflict with known satellites, planned spacecraft trajectory data must be provided in considerable detail and continuously updated to account for delays and weather effects. The trajectory data must be provided as follows:

Three-sigma launch trajectories to the point where effective thrust of the final stage is terminated to place the spacecraft in orbit. This data includes considerations of maximum achievable turning angles, vehicle aerodynamic stability or instability at various angles of attack, and other performance envelope data that can help launch-control personnel make real-time safety decisions.

a. Nominal apogee, perigee, inclination, and period of orbits to be achieved. Time, altitude, and latitude and longitude of the spacecraft's sub-point for post-injection events such as ignition, cutoff of each stage, separation of payload, re-ignition of upper stages, etc.

b. Nominal state vectors (x, y, z, x dot, y dot, z dot, t) at the beginning and end of each thrusting phase, and the state vector for any separated stage or component at the beginning of its final free-flight phase.

c. Estimates of the three-sigma drag corrected impact dispersion area (footprint) for each stage, reentry vehicle, and jettisoned component.

3.2 Operational Steps to Minimize Risks

Launch-control agencies such as the Eastern and Western Ranges have initial responsibility to ensure those missiles and spacecraft launched from their ranges avoid manned and man-able spacecraft already on-orbit. These agencies perform that responsibility by collecting current launch trajectory data from the program or test office and comparing it with satellite positional data from Cheyenne Mountain Operations Center to ensure that the proposed trajectory does not pass too close to any manned spacecraft. Launch control agencies specify that a launch be planned so that the trajectory of a spacecraft or missile will not pass within a spherical radius (close approach) of 200 km of manned objects. Launch control agencies can also request appropriate subsets of the database (orbital element sets), and run computer simulations of the launch trajectory to ensure that launch and early-orbit maneuvers will not encounter known orbital objects.

Mission Assurance Collision Avoidance (COLA) is also performed when requested by the Program Office. Mission Assurance close approach analyses (between the planned launch trajectory and either the entire space object catalog or only active satellites) are frequently desired by the payload office; however, the only mandatory conjunction analyses for all launches are the Range Safety COLA analysis mentioned

above. For Mission Assurance COLA analyses, dispersion data are used to derive the COLA screen dimensions. This is important since it specifies the uncertainty in the trajectory and is used to determine the region within which conjunctions are likely to occur. An example of a Mission Assurance Launch COLA analysis is shown in Figure I-1.

OBJECT NAME	OBJECT #	LAUNCH CLOSE	HOLD (Z) OPEN	DISTANCE (km)	TIME (s MET)	PROBABILITY
A. COSMOS 1275 DEB	13021	19:17:01	19:18:58	6.1	2081.1	3.1E-007
B. ISS (ZARYA)	25544	21:36:01	21:38:59	168.6	1409.0	SAFETY HOLD
C. MIR	16609	21:50:01	21:51:59	196.9	755.9	SAFETY HOLD
D. ARIANE 44LP DEB	19951	22:42:01	22:43:59	8.6	11981.3	2.0e-006
						Cut-off probability 1.0e-007

Figure I-1. Example Mission Assurance Launch COLA Analysis.

3.3 Assessment Tools

Flexible orbital-analysis software and access to SSN catalog data are needed for accurately assessing the risk or avoiding a collision with known satellites. There are many analytical tools in use today amongst government agencies in addition to the many commercially available tools used by agencies that control commercial satellite constellations. U.S. Space Command maintains the Space Object Catalog and the Cheyenne Mountain Operations Center (CMOC)/Space Control Center (SCC) is the primary agency within U.S. Space Command that assesses the collision risk for launch or on-orbit maneuvers.

Requirements for orbit analysis software should include the following:

- Capability to accept tracking and orbital data (ephemerides) of widely varying format and expected accuracy (one sigma, two sigma, or three sigma),
- High-fidelity modeling of gravitational perturbations, neutral particle winds, and atmospheric drag,
- Allow integration of periodic updates of atmospheric drag data or more complex high-resolution atmospheric drag models,
- Utilities to efficiently calculate and display probabilities, spherical errors, confidence levels, etc.

4. Hazards from Meteoroids and Orbital Debris

Meteoroids are naturally occurring debris objects. They generally move in heliocentric orbits and, when they sweep through Earth orbital space, can pose a hazard to Earth orbiting satellites. The meteoroid threat can be categorized into three general areas:

a) Sporadic Meteors

   The background meteor environment ("sporadic meteors") consists of those particles resident in solar system space that are not associated with any particular comet. They are the remnants of comets that have dissolved over time and the residue of asteroid collisions. The mean relative velocity of the sporadics with respect to the Earth is approximately 20 km/sec. Observational data indicates that, at any one time, about 200 kg of meteoroid mass is within 2000 km of the Earth's surface. Most of this mass is in meteoroids about 0.01-cm in diameter and larger.

b) Annual Showers

   As comets pass close to the Sun, the Sun heats the nucleus of the comet. As the surface heats up, particles will extrude from the comet. These particles will closely follow the orbit of the comet for centuries, spreading out along the orbit as time goes on. If the Earth happens to pass through this tube of dust during its yearly orbit around the Sun, an annual shower results. These meteoroid particles can have velocities relative to the Earth of anywhere from 3 to 75 km/sec. The low velocity particles can produce impact damage on satellites, but the danger from the high velocity particles is in the plasma generated as the particle vaporizes upon impact. The plasma can disrupt spacecraft electronics and kill the vehicle without causing significant physical damage.

c) Outbursts

   Meteor outbursts are characterized by transient events of unusually high activity. They are typically associated with known meteor streams (annual showers). The Leonids of 1998-2001 are of this type. The parent comet of the Leonids, P55/Tempel-Tuttle, travels around the Sun once every 33 years and last passed perihelion in early 1998. As a consequence, the fresh particles from this passage (and several recent passages) are still close to the comet's orbit. Since they have not yet had time to disperse, the result is a high concentration of particles in the Earth's path. Outburst particles pose the same type of danger as the annual showers due to the potentially very high velocities. However, an outburst can produce numbers of particles that are several orders of magnitude greater than the associated annual shower.

The following figure shows the meteoroid threat as a function of solar longitude. The flux refers to the number of dangerous particles per second per unit area where the danger is determined by the particle's density, size, and velocity. Since different meteor streams have different relative velocities, what constitutes a dangerous particle will vary widely between streams. The dangerous flux as shown here accounts for this variation. Several of the annual showers present threats that are similar to the background sporadics, but overall, the sporadics present a larger danger than the cumulative annual showers. Also shown is the Leonid storm of 1966. This depicts the relative danger that a meteor outburst can exhibit; the 1966 flux was several orders of magnitude larger than the usual Leonid threat. While short lived, the particle flux was extremely dangerous during those few hours.

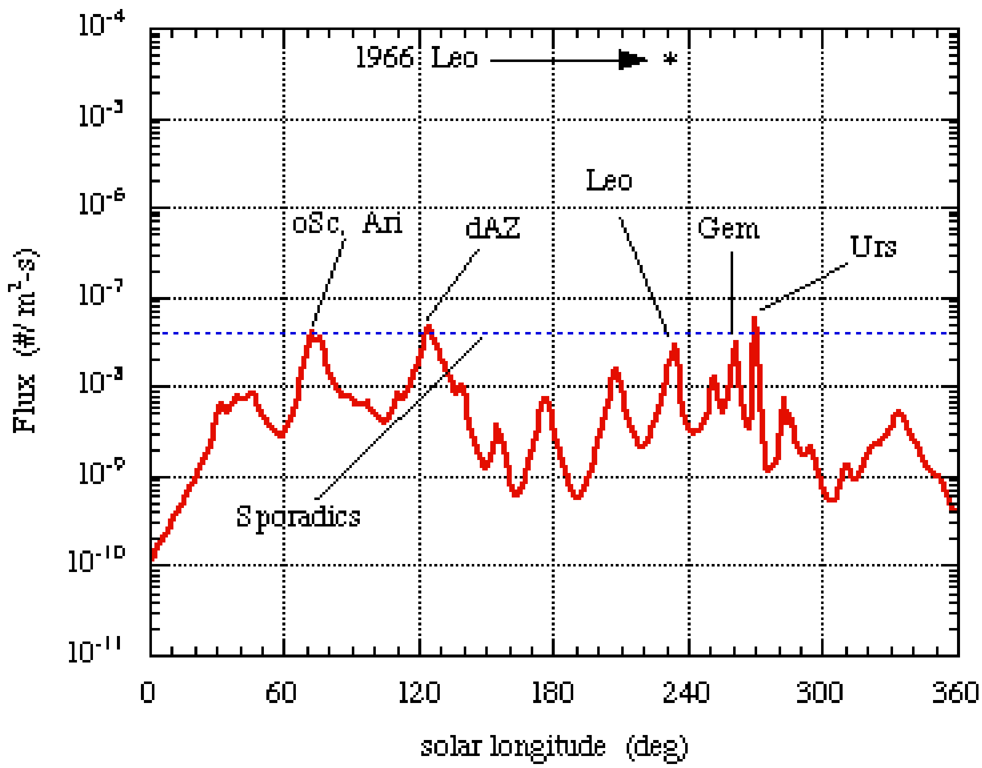

Figure I-2 Meteoroid Threat vs. Solar Longitude

Orbital debris consists of many man-made objects placed into Earth orbit, which are not operational, or no longer serve a function. It can be categorized by source as follows (ref. IA Report on Orbital Debris 1995):

a) Operational Debris
Consists of inactive payloads and objects released during satellite delivery or satellite operations, including lens caps, separation and packing devices, spin-up mechanisms, empty propellant tanks, spent and intact rocket bodies, payload shrouds, and a few objects thrown away or dropped during manned activities. This type of debris is decreasing due to more space environment friendly designs being adopted that no longer release such objects.

b) Fragmentation Debris
This type of debris usually results from explosions or collisions. Despite active efforts of spacefaring nations to reduce the probability of such events occurring by passivating their systems at end of mission, the number of events has been continuing at a fairly sustained level. Since the first detected fragmentation of the Omicron rocket body in June of 1961, 156 fragmentation events have been documented. In the last ten years the number has ranged from 4 to 8 per year. There are several potential contributors to explosions including (1) the catastrophic failure of internal components such as batteries, (2) propellant-related explosions (high-energy explosions), (3) failure of pressurized tanks (low energy explosions), and (4) intentional destruction. Collisions with other orbital objects may also cause fragmentation. Only one natural collision of cataloged earth objects has been confirmed to date. On 24 July 1996 a fragment from a European Space Agency (ESA) Ariane rocket body collided with the French government's CERISE spacecraft's gravity-gradient boom, severing the vital

appendage in half. Both objects were in nearly identical retrograde orbits at the time of the event. The spacecraft remains operational with a degraded attitude control system.

c) Deterioration Debris

The gradual disintegration of spacecraft surfaces as a result of exposure to the space environment produces very small debris particles such as paint flakes and small bits of plastic and metal erosion. Even small paint flakes can do damage in space as can be seen in the widely reported impacts on the Space Shuttle windows. This type of debris is not limited to smaller objects. Several orbital objects such as Ariane upper stages and Russian Proton upper stages in GTO have been observed to periodically shed materials such as deteriorating thermal blankets and insulation over long periods of time.

d) Solid Rocket Motor Ejecta

Thousands of kilograms of aluminum oxide dust are released into the orbital environment every time a Solid Rocket Motor (SRM) is used to transfer objects from LEO to GEO. This dust, although very small, is likely to cause erosion of exterior surfaces, chemical contamination, and operational degradation of vulnerable components such as optical windows and solar panels during long-term exposure. Chemical analysis of impacts on the Long Duration Exposure Facility (LDEF) spacecraft indicates that a significant fraction of the impact craters contain traces of aluminum. These particles, however, usually decay very rapidly due to their large retrograde velocities, low mass and low altitude orbits. Consequently the operational threat of SRM dust is probably limited to brief periods of time related to specific mission events.

4.1 Design Considerations

The effects of particle impacts whether meteoroid or debris depend on particle velocity and mass. For debris sizes less than 0.01 cm, surface pitting and erosion are primary effects. Over a long period of time, cumulative effects of individual particles colliding with a spacecraft might become significant, since the number of particles in this size range is very large, especially for orbital debris in LEO.

For debris between 0.01 and 0.1 cm, damage effects are spacecraft design dependent. There are certain surfaces that can be penetrated by debris in this size range such as radiator heat pipes on a spacecraft for which analysis was recently conducted.

For debris larger than 0.1 cm, spacecraft structural damage becomes important. For example, a 0.3-cm sphere of aluminum traveling at 10 km/sec has about the same kinetic energy as a bowling ball traveling at 60 miles per hour. It is reasonable to expect significant structural damage to spacecraft if a collision occurs. Mitigation guidelines require the identification of any debris objects greater than 5 mm (0.5 cm) in any dimension that are planned to be released during normal operations and have a nominal orbital lifetime of 25 years or greater. The value of 5 mm represents the approximate debris size limit that a spacecraft's ¼ inch aluminum wall can withstand in a collision without catastrophic breakup.

Some meteoroid relative velocities can approach 75 km/sec. When these high velocity particles hit a spacecraft, the smaller particles will vaporize into plasma. Instead of causing structural damage, the plasma carries the ability to short out electrical systems on the vehicle. Since smaller particles are much more numerous than larger ones, plasma discharge is actually as great a problem for high velocity meteoroid impacts as structural damage.

Principal techniques used to mitigate the effect of collision with debris and meteoroids are careful placement of critical components, shielding and redundancy. An important design consideration is the protection of hardware needed for end-of-life maneuvering to disposal orbit or reentry. Even lightweight shielding provides a significant risk reduction, since the probability of being hit by smaller particles (because of their greater population) is much greater than that of being hit by larger particles.

Currently it is impractical to shield against debris particles up to 1 cm in diameter due to weight penalty. Only for manned spacecraft is it feasible due to the high cost. Advanced shielding concepts may make shielding against particles up to 2-cm diameter reasonable. Collision avoidance is the only useful alternative for trackable debris. For single, average size spacecraft, the probability of collision is usually very small. For constellations or large spacecraft, especially long-duration ones like the International Space Station, collision probabilities are sufficiently high that collision avoidance is required.

Future DoD LEO spacecraft must be designed for a factor of two longer lifetime than the current LEO spacecraft, both DoD and commercial. Current LEO spacecraft were not designed to survive the possibility of debris and meteoroid impact, as well as contamination exposure for the length of time they are remaining in orbit. The Long Duration Exposure Facility (LDEF) showed conclusively that damage to spacecraft materials from meteoroids, contamination and atomic oxygen is significant. Another concern for current and future spacecraft is the fact that man-made debris and released chemical populations in LEO are likely to increase at a higher rate, since most LEO missions will involve large constellations of small space vehicles. There could also be a larger deployment of so-called Micro-, Nano-, and Pico-Sats in the near future. These small satellites may be classed by mass, with Micro-Sats weighing 100 kg or less, Nano-Sats 10 kg or less, and Pico-Sats 1 kg or less.

4.2 Operational Steps to Minimize Risks

For individual meteoroid events such as the Leonid storms, several operational strategies can be employed to dynamically mitigate the danger posed by the particles. The most obvious way of completely avoiding the Leonids or any other transient meteor threat is simply to delay a launch past the time of the event and thereby dodge the issue entirely. Of course, if the meteor events regularly occur in time, such as the annual showers or background sporadics, this tactic is not very effective. If, however, the event is singular, such as a meteor storm caused by the reappearance of the parent comet, then avoiding the threat by delaying the launch is indeed a viable option, provided more important mission constraints are not violated. But this is not a practical alternative for satellites already on orbit. Because past meteor events have been known to damage spacecraft to the extent that mission operations were significantly degraded or even completely lost (i.e. a Perseid hit on Olympus I in 1993), solutions to the on-orbit problem are most crucial.

The simplest way to reduce the risk of negative mission impact for a transient meteor event is to safe the vehicle during the time of the storm. This reduces the probability that plasma discharge will hurt the vehicle's electrical systems. One easily implemented mitigation strategy is to alter the attitude of the spacecraft or solar panels in order to minimize the cross-sectional area that is presented to the oncoming meteors, thereby reducing the probability of an impact. A related option is to orient the spacecraft so that the flux that penetrates a vehicle's shielding is minimized. This damage minimization is potentially distinct from area minimization. Other more exotic ways of reducing the threat consist of in-plane orbit maneuvering to reduce the relative velocity between the spacecraft and the meteoroids or orbital maneuvering in general to place as much distance as possible between the spacecraft and the center of the meteor stream. Out-of-plane maneuvering can also be performed to place the node in a position that takes advantage of the Earth's shadowing. Operational considerations are unique to each type of spacecraft and mission; practicalities will influence the applicability of any potential mitigation strategy[15].

Selecting an orbital altitude where the debris population is less dense is the main operational step that can be taken to minimize the risk of collision with man-made debris. Debris hazards should be made a part of trade studies to select an altitude for test missions. Larger pieces of debris, whose locations are known,

[15] Dynamics of Meteor Outbursts and Satellite Mitigation Strategies, Glenn Peterson, Aerospace Press, 1999

can be tracked and avoided as is done with operational satellites. The SSN can also be tasked to survey certain orbital altitudes for debris, and planners can refine pre-mission risk assessments.

Other operational steps can be taken to limit the introduction of more debris in orbit. Typically, they support the design consideration and fall into two broad categories:

a. More intensive mission planning and on-board system monitoring to ensure that mishaps are avoided. In Volume II of this Appendix, paragraph 2.0 lists design features to avoid explosions. There are also corresponding monitoring procedures to avoid an explosion mishap that are primarily developed by system-safety and other system-engineering personnel during the design process.
b. Experiment or test scenario design to minimize the risk of major hazards. This level of planning involves selecting engagement geometry, orbits, and altitudes that provide valid data at less risk. It involves defining go-no-go performance criteria, abort windows, and keep-out areas.

4.3 Assessment Tools

In order to assess the hazard posed to a mission by meteoroids and debris, environmental models and damage assessment tools are required.

For modeling the sporadic meteoroid environment, two models are readily available. The Grün model was developed in 1985 and is the current standard model at NASA for space vehicle design analysis. It produces meteoroid background flux vs. meteoroid mass. The MASTER 99 model is the current standard at the European Space Agency (ESA) and produces a wider variety of data, including detailed velocity and direction distributions. It also accounts for more recent meteor radar survey data, which is not reflected in the Grün model. Finally, it has the capability to model specific meteoroid streams such as the Leonids and Perseids.

For modeling untrackable debris (objects less than 10-20 cm in diameter), two models are readily available. ORDEM96 is a code developed by NASA Johnson Space Center that permits rapid generation of debris flux vs. size and some limited directionality information. MASTER 99 produces a wider variety of data, including detailed velocity and direction distributions. It also accounts for some additional debris sources that are not included in ORDEM96 but should be included in the upcoming release of ORDEM2000.

In order to assess damage, there are primarily three analysis methods. The first involves the use of ballistic limit equations (BLEs), which are empirically derived primarily from ground-based hypervelocity impact tests. The second involves the use of hydrocode simulations that model stress wave propagation and material deformation in penetrator (debris or meteoroid) and target (spacecraft surface) materials from first principles. The third method is to perform impact tests on spacecraft component prototypes in a hypervelocity impact test facility. The last method may be the most expensive of the three.

For assessing the risk posed by trackable debris, the U.S. Space Command catalog of Resident Space Objects (RSOs) is available for support of SMC space programs. This data, in combination with a manifest of planned launches, is very useful for collision risk analyses over the mission timeframe.

5.0 On-Orbit Maneuver Hazards

On-orbit maneuvering hazards include collision hazards associated with maneuvers, docking, extra vehicular activities, maneuvers to reenter a space vehicle, etc. These hazards result from (1) guidance errors, (2) guidance hardware failures, (3) the time delay of satellite control, caused by great distances from ground-based control centers, and (4) off nominal propulsion system performance.

Orbital mechanics constraints must be invoked to ensure smooth, accurate, and fuel-efficient maneuvers. This requires continual calculation of transfer orbits using precise orbital or relative-position data that must be updated frequently to compensate for errors. Communication delays, sensor tracking errors and computational times greatly reduce the degree of precision control that can be done from Earth and necessitate some form of onboard sensors and/or control. Any contact between two spacecraft can cause considerable damage because weight limitations impose minimum load factors in the design of spacecraft structures.

5.1 Design Considerations

Basic design considerations to reduce on-orbit maneuvering hazards involve high system reliability, redundancy, and design features to shorten control responses. Most critical are systems that control vehicle attitude and orbital maneuvers. Careful systems design and rigorous system-safety analysis, especially software safety, are keys to reducing this category of risk. Requirements for on-board sensors and autonomous controls should be derived from careful experiment and system design. Release of gases, jettisoning of hardware items, attitude control thrusting, and maneuvering burns must be carefully analyzed for momentum transfer and possible contamination from expelled particulates.

Space experiments and operational tests should be conducted at orbital altitudes that minimize risk to other satellites if a mishap occurs; e.g., loss of control, explosion, or debris impact. Selecting a little-used orbit may be more costly to a specific system or test program due to extra fuel requirements, but it may avoid harm to more expensive operational spacecraft. Table I -1 lists orbits that will probably remain highly valuable and populated and should be avoided if not mission-critical. Low altitude tests are preferable because debris orbital lifetime is shorter.

Table I -1. Highly Valuable and Populated Orbits

	Basic Orbit Type	Altitude (km)
A.1	**Low Earth**	**500 to 1200**
B.1	**Low Earth**	**1370 to 1530**
C.1	**Semi-Synchronous**	**19,000 to 20,200**
D.1	**Geosynchronous**	**35,700 to 35,900**

5.2 Operational Steps to Minimize Risk

Currently Cheyenne Mountain performs on-orbit conjunction analysis on an as requested basis. When an operations squadron is planning a maneuver, they will notify CMOC and provide them with the planned maneuver parameters. CMOC will compare these maneuver parameters against the Space Object Catalog to determine if there are any conjunctions. Maneuvers are often delayed slightly to avoid a predicted close approach.

Maneuvers must be planned in advance to ensure there are no violations of close-approach thresholds established for each active or inactive satellite. Maneuvers and object release must be planned well in advance to minimize fuel usage and avoid inadvertent momentum transfer. Detailed operational procedures must be written and practiced.

5.3 Assessment Tools

The determination of collision hazards due to on-orbit maneuvers, formation keeping, rendezvous, and docking operations, necessitates access to computational tools that allow the modeling of orbital maneuvers and relative motion time histories.

Maneuver planning algorithms (capable of simulating orbital adjusts caused by thruster activity) are a pre-requisite for assessing the hazards due to on-orbit maneuvers. To that end, data related to pre- and post-maneuver orbital state and information related to the physical characteristics of on-board thrusters are required. The pre-maneuver state vectors are derived from orbit estimation operations and are based on the processing of tracking observations. Post-maneuver state vectors are based on the spacecraft's initial orbit with the nominal velocity increment (i.e., delta-V) applied at the defined burn epoch. In some instances three sigma dispersions are used to accommodate uncertainties due to thruster performance.

To determine the effect of on-orbit maneuvers, algorithms have been developed by commercial and government agencies to simulate orbit adjust maneuvers using finite and impulsive thruster models. Typically, these models require information related to thrust magnitude, specific impulse (ISP), burn duration, thruster orientation, and the mass properties of the spacecraft. Finite models are more appropriate for thrust intervals that require extended burn duration. Post-maneuver orbit vectors are used to evaluate the spacecraft position/velocity (post-thruster activity) and to assess the collision threat posed by resident space objects. Maneuver activity and associated parameters are coordinated with CMOC in order to assist SPADOC tracking operations. Determination of ground station visibility is important to determine intervals for nominal and contingency commanding of spacecraft using TT&C resources.

Relative motion algorithms allow the determination of relative positions and velocities between two or more orbiting bodies. Data elements that are generated during relative motion studies include the time history of slant range, relative velocity magnitude, and range-rate. The slant range and relative velocity magnitudes are typically resolved into components of radial, in-track, and cross-track relative to the reference body's position and velocity. The use of high-precision, orbital propagation models is essential for modeling perturbations due to the atmosphere, sun/moon and earth's gravity field. For extended

intervals of propagation, high-precision models minimize the uncertainty of a spacecraft's position and velocity during the defined time span for evaluating potential hazards.

6.0 Hazards from Reentering Objects

Reentries may be classified as controlled or uncontrolled allowing for a sometimes-fuzzy distinction depending upon the degree of success in predicting an impact point. A controlled reentry is a planned reentry in which the spacecraft is given a delta-V to kick it into a new, lower-energy (and often more elliptic) orbit that penetrates the Earth's atmosphere far enough to ensure that any surviving components reenter and impact in a planned area, usually within one revolution (e.g., perigee altitude <20 nm). The greater the delta-V, the more perigee altitude is lowered, and the less time there is for errors in predicted atmospheric lift, drag, and winds to cause the spacecraft to vary from its planned impact point. An uncontrolled (random) reentry is one in which the orbit is allowed to decay until the spacecraft spirals deep into the atmosphere and aerodynamic drag is sufficient to deorbit it. A controlled reentry can become an uncontrolled reentry if control of the spacecraft is lost or the impact point can no longer be controlled enough to ensure safety. A controlled reentry assumes the reentering body is tracked by ground stations prior to (and usually during) reentry. An uncontrolled reentry body may or may not be tracked depending on its radar cross-section or luminosity. Many smaller pieces of debris are never detected and randomly reenter.

Orbital decay of spacecraft, boosters, and other components pose a worldwide hazard to life and property. The Air Force has adopted a policy that all orbital vehicles should be safely reentered into the atmosphere or be moved into a disposal orbit at the end of its useful life to reduce the risk of leaving a structure near an operational orbit regime.

To assess the risk from reentering objects, two areas should be considered: risk analysis and reentry scenario.

a. The basic approach to analyzing the risks posed by a reentering spacecraft consists of answering three questions: (1) how long will it stay in orbit, (2) when it does reenter, will all or some of it survive reentry to impact the earth's surface, and (3) if it does survive, what is the casualty expectation?

   (1) The length of time that an object will stay in orbit is a function of many variables, such as apogee altitude, perigee altitude, inclination, atmospheric density, object weight, size, etc. In general, it can be stated that lightweight, high-drag objects, such as an old circuit board in very low Earth orbit, will stay in orbit only a few days. On the other hand, a heavy, low-drag payload boosted into a higher orbit may not reenter for hundreds of years. The duration of time that the satellite has left in orbit has a direct influence on the reentry prediction accuracy. As lifetime increases so does the uncertainty as to when reentry will occur and where it will impact.

   (2) Reentering objects may either break-up into fragments during reentry or survive largely intact. Breakup occurs when accumulated heat weakens the spacecraft's structure to such an extent it cannot withstand the the forces experienced during reentry. This process usually occurs quickly within a narrow altitude band between 70 and 85 km. Three types of objects may be expected to survive reentry. First are those designed to survive reentry by using thermal shielding along with appropriate shapes (e.g., STS Orbiter or Apollo command capsule). Second are spacecraft components made of materials with high melting temperatures such as titanium, beryllium, stainless steel, etc. (e.g., propellant tanks, structural supports, batteries). Third are objects with very low ratios of weight to drag (e.g., circuit boards, and antennas). Reentry heating analyses can be performed to establish probable characteristics of surviving components/fragments or engineering judgement can be used to estimate survivability of the hardware components. From these sources, a profile of characteristics (size, weight, atmospheric drag, etc.) for impacting debris can be estimated and subsequently used in the hazard calculation.

(3) To determine the level of risk to people and property from surviving debris, the first step is to define the extent of the debris area. If it is a planned reentry, the goal is to have the debris impact footprint extend over a broad ocean area. The risk in terms of injury to people will then be essentially zero. The risk posed by reentering debris, whether rocket bodies or spacecraft has traditionally been couched in terms of expected casualties from a specific reentry event. Typically, the debris fragments surviving reentry are estimated and converted to a total casualty area. Casualty expectation can then be estimated by applying the casualty area to the population distribution over the estimated impact area of the debris. For a random reentry the impact area is confined by the orbital inclination of the parent body, while for a targeted reentry the impact area lies within a better-defined debris footprint. The casualty area is based on the dimensions, weight, etc. of the impacting object/objects and the type of reentry.

b. Various types of reentry scenarios can be summarized based upon the degree of control, type of objects, and breakup mechanism involved. The following categories describe most reentry scenarios:

(1) Controlled (planned)
  (a) Guided (internally guided or commanded from ground such as the STS Orbiter)
  (b) Unguided (no maneuvers, such as the STS external tank, or only a de-boost delta-V used to lower perigee, such as a LEO satellite)

(2) Uncontrolled (random, natural orbit decay)
  (a) Tracked (by ground sensors, etc.)
  (b) Untracked

6.1 Design Considerations

Air Force Instruction 91-202 states that orbital systems shall be designed to minimize the generation of orbital debris during and after their service life. Vehicles should be safely reentered into the atmosphere or be moved into a disposal orbit at the end of its useful life. End-of-life safing actions for systems disposed of in space include, but are not limited to, venting all pressure vessels, safing batteries, safing any remaining ordnance systems and turning off any transmitters.

Design options to reduce reentry hazards must be carefully applied to each planned experiment or mission. Hazards from reentering spacecraft or test objects can be almost eliminated by designing them to be:

(1) Boosted into disposal orbits or deep space
(2) Almost totally destroyed and consumed during reentry so that remaining particles are relatively harmless
(3) Controlled throughout the reentry or targeted so that any surviving material lands in a safe area

6.2 Operational Steps to Minimize Risks

Planning safe reentries requires accurate models to do trade studies and evaluate the risks involved. Both controlling the spacecraft and predicting the behavior of the debris require high-fidelity mathematical models that have the capabilities to:

(a) Describe the probable results of a breakup, (explosion, collision, kill mechanism or reentry) in terms of the number and distribution of debris particles by size, weight, ballistic coefficient, toxicity, and velocity.
(b) Describe the probable reentry footprint.
(c) Evaluate ground paths and test locations where data collection is possible and expected reentry footprints are acceptable.
(d) Use multiple burns to calibrate propulsion system if possible.

(e) Assess the consequences of an under- or over-performing deorbit burn.

6.3 Assessment Tools

NASA, ESA, and SMC, as well as several contractors are developing software tools for the evaluation of the risks of reentering hardware. The major complications affecting the prediction of risk are:

(1) Modeling the aerothermal environments that both reduce the structural integrity of the spacecraft as well as reduce the amount of survivable debris.

(2) Developing a thermal/structural computer model of the reentering spacecraft and its components that is able to accommodate the dynamic reentry environment (i.e., materials being ablated or shed).

(3) Modeling the lift forces that disperse the debris and determine the size of the impact footprint.

Requirements for casualty expectation software should include a probabilistic description of the (casualty) area resulting from the spacecraft breakup and a probabilistic description of the debris footprint size and shape – equivalent to probability density.

Volume II - Explosion Hazards

1. Introduction

Many spacecraft systems and components operate at high pressure or may be subjected to electrical or mechanical overloads that can release destructive energy. An explosion can produce other hazards such as collision with debris or chemical and radiation contamination that place large numbers of people at risk. In fact, many hazard categories in this document can be directly or indirectly related to explosion hazard, either as an external source or a mishap producing an explosion, or a follow-on hazard created by an explosion mishap.

To ensure explosive safety, the Air Force and other agencies established a comprehensive series of directives covering all aspects of design, manufacturing, handling, transportation, storage use, and disposal of explosive material and devices. Air Force Instructions (AFI) series 91 (Safety) and 99 (Armament) apply to explosives used for non-nuclear applications. Whenever explosives are employed as part of nuclear munitions, compliance with the 91 series of AFI and the provisions of Air Force Technical Order (AFTO) 11N-20-7 is mandatory for Air Force programs.

2. Design Considerations

Generally, there are four "levels of protection", or sequence of steps usually taken to avoid or limit damage from most hazards. These four lines of defense are particularly appropriate to explosions:

a. Strict design, testing, or quality control standards for subsystems or components that have a potential to explode.
b. Use of protective devices, shields, venting systems, etc., to limit immediate effects of energy release.
c. Design and testing of other subsystems to reduce collateral damage and avoid producing subsequent hazards.
d. Use of operating procedures, restrictions, etc., to avoid or contain hazards triggered by an explosion.

Safety must be designed into a spacecraft. The "levels of protection" should be basic system safety requirements that are integrated into development programs in consonance with other system performance requirements.

3. Operational Steps to Minimize Risks

Operational procedures should be developed to monitor and control spacecraft systems in order to avoid an explosion or to limit the consequences if one were to occur. These procedures are, or should be, the result of the system engineering process that continues throughout the spacecraft's development and testing. System safety personnel play their traditional role throughout the establishment of these operational procedures. They maintain the safety perspective, do safety audits and hazard analyses, and help write procedures.

4.0 Assessment Tools

Designers and manufacturers of explosive devices and other hardware items with a potential to explode (pressure vessels, electrical components, etc.) have devised a variety of general purpose and system-specific models to predict the probability of an explosion or to explain the physical mechanisms involved in an explosion. SMC System Safety personnel work closely with the designers and manufacturers so that they can produce independent assessments of the ultimate consequences of an explosion.

Volume III – Directed Energy Hazards

1. Introduction

Directed energy devices are defined as systems that emit highly collimated, energy-carrying beams that may be ionizing. The areas of primary concern are: (1) inadvertent damage or destruction to manned or unmanned spacecraft, (2) interference of the directed energy beam with spacecraft operations, and (3) harm to the general public.

2. Lasers

Lasers are used or planned for a variety of applications in space: communications, surveillance, anti-satellite, defensive satellite, strategic missile defense, and others. Lasers can be ground-based, aircraft-based, or space-based. Some advanced laser concepts use space-based relay mirrors to route the beam around the earth, or ground-based with a space-relay mirror system. Typically, the various types of lasers are distinguished by application, waveform (pulse width and duty cycle), pulse width (or duty cycle), power (or energy), wavelength (or color), and method of generation. There are three categories of laser waveforms that are generally used today:

(1) Continuous Wave (CW) Lasers – These lasers operate in a steady-state mode and provide power continuously, can be space-based, ground-based, or ground-based with a space-relay mirror system. An example of this type of laser is the chemical oxygen iodine laser (COIL), which was developed for military applications by the Air Force beginning in the late 1970s. The laser works by creating an electronically excited state of oxygen, called oxygen singlet delta. Energy from the singlet oxygen transfers to atomic iodine. The excited iodine then emits light. Because COIL is a low-pressure flowing gas laser, heat is removed from the lasing medium very quickly. Also, the design can be scaled up to achieve higher powers, as have been demonstrated by AFRL.

(2) Single Pulse Lasers – These lasers are designed to provide a very high-powered beam over a short interval. These devices are either single-shot or can be multiple-shot if there is sufficient time to recharge the energy storage device (typically some sort of electrical capacitor or inductor, or perhaps a flywheel generator). Most of the single pulse lasers that the Air Force has built are chemical lasers or explosively driven lasers.

(3) Repetitive Pulse Lasers – These lasers are a hybrid between continuous wave and single pulse lasers. The energy delivered by each pulse is considerably less than a single pulse laser but the pulses can be delivered continuously and total energy is comparable. A continuous power supply is needed to deliver the multiple pulses, which typically tends to be heavy since it requires not only a capacitor, but also electrical generating equipment.

Laser tests may be performed in any one of three configurations with specific areas of concern: (1) ground-to-space where interference with satellite sensors and (for high-powered lasers) scattered radiation are prime considerations; (2) space-to-space where continual motion and uncertainty in beam trajectory require precise determination of source and target orbits and other satellites that may be endangered; and (3) space-to-ground where containment of harmful radiation within a safe geographic region or airspace is essential. For all types of lasers, errors in pointing, inadvertent slewing, loss of focus, focusing error, atmospheric scattering, beam refraction, and premature firing must be addressed. For medium and high power lasers, the possibility of physical destruction must be considered for thermal, electromagnetic, and electrostatic discharge effects. The hazards associated with lasers include biological effects (burns, eye damage, skin reactions, distress, etc.) to humans and animals, heating effects, and the disruption of photosensitive devices and unprotected semiconductor devices on spacecraft or other irradiated assets.

Lasers can be divided into three general categories based on power and consequent hazard level:

a. Low-power devices – Lasers typically used in applications where it is intended that a detector be directly illuminated by the primary laser beam, e.g., communications or laser beacons. Very little intensity of illumination is usually required in such applications, and there is often no hazard beyond the immediate vicinity of the beam source.
b. Medium-power devices – Generally used in applications where the intent is to detect a passively reflected or otherwise re-radiated signal from a non-cooperative target, e.g., laser trackers, rangefinders, discriminators, and target illuminators. The primary beam must have orders of magnitude greater intensity than a low-power device to provide a usable return signal to the detector. Consequently, it is likely to be hazardous even at very long ranges in the absence of atmospheric attenuation.
c. High-power devices – Weapons-grade lasers intended to produce physical damage in targets. The primary beams are hazardous under virtually all circumstances and even reflected or scattered radiation may be hazardous at considerable range.

With regard to biological hazards to humans, detailed criteria developed for ANSI Standard Z136.1 Safe Use of Lasers, have been widely accepted and adopted in whole or in part by the military services and NASA.

2.1 Design Considerations

System designers can minimize the hazards of directed energy devices by complying with the following design goals:

a. Any spacecraft containing a directed energy device must be designed to provide a high degree of stability for accurately aiming the device. Telemetry must be provided to verify stability before critical actions are taken.
b. Positive optical stops must be used to limit the beam spread of the device. The reliability of the system to stay within the field-of-view must be established and included in design specifications.
c. A termination system such as a laser window shutter must be included in all systems capable of causing a catastrophic mishap. Automatic fail-safe beam termination systems will be used to terminate testing in case of beam director failures/errors, navigation and orientation failures/errors, or failure to verify lock on target.
d. Design of targets must limit debris generation and eliminate specular reflective surfaces for which uncontrolled beam reflection could prove hazardous.
e. Precise position/orbit determination is needed for test spacecraft as well as for unrelated neighboring spacecraft. Smaller test articles may require tracking aids, e.g., coherent transponder to ensure precision.
f. Automatic safety features aboard a spacecraft should be capable of notifying the operator of the action taken, and should allow operator overrides.
g. Tests must demonstrate conclusively that dynamic systems can be controlled and kept within imposed operating tolerances.
h. When energy in excess of that allowed by American National Standards Institute (ANSI) standards may irradiate the Earth, test sequences must be carefully planned and coordinated among the participating ranges. Hazard limit lines must be established, and warnings must also be issued to airmen and mariners.

The development of high-powered lasers, and increasing use of other lesser-powered lasers, poses a potential risk to the ever-increasing number of orbiting satellites. The inadvertent laser illumination of a satellite could either temporarily or permanently harm a satellite's ability to perform its mission.

To address this concern, DoD Instruction 3100.11 was recently signed directing all DoD components to conduct laser activities in a safe and responsible manner that protects space systems from any potential harm that could be cause by such inadvertent illuminations. The DoD Instruction also states that it is the responsibility of the U.S. Space Command's Laser Clearinghouse (LCH) for coordinating and supporting the safe and responsible conduct of all DoD laser activities.

2.2 Operational Steps to Minimize Risk

Detailed pre-mission planning and coordination is required for all missions. Avoidance regions must be defined around all test objects such that penetration into that region presents an unacceptable risk to the test object, penetrating object, or both objects.

Capability for prevention of inadvertent beam activation should be provided for all test operations. This capability consists of automatic fail-safe systems to assure safe shutdown or firing lockout in case of failure or errors: in (1) beam direction, (2) navigation/orientation, and (3) target lock-on. Developing an appropriate experiment scenario and supporting operational procedures should be key parts of a system-safety process.

2.3 Assessment Tools

DoD software tools for laser hazards are under the purview of the Laser Clearing House. The Laser Clearing House at the Cheyenne Mountain Center is currently responsible for safeguarding orbiting satellites from DoD laser hazards. A software tool is currently in operation at the Cheyenne Mountain Center that protects satellites by geometrically deconflicting (i.e., through predictive avoidance) lasers and satellites.

High-power laser lethality assessment tools are under the purview of the Missile Assessment Center, AFRL/DEL, at Kirtland AFB. Under this center is The Laser Effects Test Facility, AFRL/DELE. This is the center of the AF's work on the lethality of high-powered lasers against virtually all targets -- ground targets, air targets (strategic and theater missiles, aircraft, cruise missiles), and space targets (post-boost vehicles, RVs, RV decoys, satellites and their components). AFRL/DEL has several computer codes they use in their work, as well as an extensive database of test results. Some of the key computer codes they have developed are RPHEL (Repetitively Pulsed High Energy Lasers; this code also handles CW lasers), ITRAL (Integrated Target Response Algorithm), SABRELITE (this code has "fragility curves" and is used for statistical shot line analysis for generating the Probability of Failure of components in the path of the laser beam; It is generally used for targets with several subsystems such as PBVs and satellites) and HITS (a Monte-Carlo code that generates Probability of Kill for a target as a function of the incident laser fluence -- Joules/cm2).

Volume IV – Electromagnetic Interference Hazards

1. Introduction

Electromagnetic Interference (EMI) is radiated electromagnetic energy that is foreign to the affected system and is potentially harmful. Another definition of EMI is electromagnetic impulse which is generated by nuclear explosions. Sources of EMI include communications and telemetry transmissions, radars, directed-energy devices (lasers and particle beams), and the natural space environment. Radio Frequency Interference (RFI), electrostatic discharge (ESD), electrical transients, and surges are common types of EMI. Electromagnetic effects on a spacecraft could result from other spacecraft fly-bys, normal space-based EMI, ground-based EMI impingement, hostile EMI, and EMI as a result of an experiment. The probability of EMI increases as the number of orbiting spacecraft increases, causing spectrum crowding in a number of frequency bands.

EMI has an impact on how well information in data is collected by remote sensing satellites as well as how well data is transmitted to communication satellites. Two quantities that describe the performance degradations caused by EMI interference are signal-to-noise ratio (SNR) and bit error rate (BER). Satellites that have remote sensing detector systems can be subjected to higher noise levels from EMI and therefore have lower SNR performance. Similarly, satellites that rely on the radio frequency spectrum bands susceptible to EMI interference can have higher bit error rates causing a loss of correct bits in the data stream.

Natural sources of EMI are very serious problems because they are difficult to predict and control. The following are some major sources:

a. Solar activity – The sun constantly emits both electromagnetic radiation and corpuscular streams. Both types of emissions are more intense during solar flare activity. The flux of solar particles interacts with the Earth's geomagnetic field to form the giant, complex structure called the magnetosphere that impedes the direct entry of charge particles from the Sun. Within the magnetosphere we have the plasmasphere and the complex radiation belts. Closer to the Earth we have the ionosphere with its "D", "E", and "F" layers that either allows signals to propagate through or reflects them, depending upon their frequency, solar activity, local time of day, and other factors. All of these physical phenomena are influenced by solar activity that can directly affect a spacecraft or transmissions to or from a spacecraft in ways that can produce mishaps.

b. Cosmic rays – Cosmic rays are high-energy corpuscular radiation consisting primarily of protons and electrons originating from the Sun or outside the solar systems. Cosmic rays generated by solar flares pose the most serious threat to man and equipment. Since the amount of required shielding is currently impractical, mission planning and scheduling must handle hazard mitigation.

Effects caused by the ionosphere (beginning about 50 km above the Earth's surface) are sometimes referred to as atmospheric effects. Its "D", "E", and "F" layers move in and out and fade and reappear in response to solar activity, and have a very significant influence on many communications signals. Other atmospheric effects include electrostatic discharge (lightning), ducting (beam bending) due to density change or electric fields, and attenuation due to precipitation and molecular resonance of atmospheric gasses. All of these can produce EMI or allow extraneous signals to become EMI. They can interfere with communications between spacecraft and ground stations and interfere with the performance of remote sensing spacecraft.

2. Design Considerations

Consideration must be given to the electromagnetic environment from both friendly and hostile emitters that a platform may encounter during its life cycle. Hostile emitters are typically considered through threat-based scenarios. Subsystems should be designed for maximum EMI hardness consistent with mission and cost. Placing a limit on the amount of interference that can be issued at the source and/or reducing the susceptibility of the receiving circuit can control EMI. Efforts to avoid EMI are basic system design and engineering functions that range from defining the requirements and operating environment, to selecting appropriate electronic components and shielding techniques.

Spacecraft must be designed to function in the anticipated EM environment. Areas of concentration in design analysis might include:

a. Spacecraft and ground station transmitters and their operating characteristics, including number, type, power levels, frequency, and bandwidth attributes
b. Antenna gains, beam patterns, pointing accuracy, and scan characteristics
c. Sensitivity of receivers bandwidth, spurious signal rejection
d. Inadvertent transmission path
e. SNR of remote sensing detectors and BER of satellite data transponder systems

An EMI evaluation should include a review of supporting ground stations and their operating characteristics; including location, transmitter power, and bandwidth.

3. Operational Steps to Minimize Risk

Most EMI reduction can be accomplished by careful design of electromagnetic systems. Additional EMI reduction can be realized by careful mission planning and design review of important performance specifications.

4. Assessment Tools

Accurate predictions of EMI hazards can be made using the same relative motion assessment tools that are applied to physical collision avoidance analyses. Such tools rely on predictions of locations of combinations of ground locations and/or space objects that can broadcast, receive or interfere with one another. Some such tools model the EM interference using keep-out cones, which determine the minimum angle between apparent positions of a transmitter and interferer as viewed from the receiver. Other tools model the gain of the receiver using varying methods to directly determine the impact of interferer signal strength on the receiver/transmitter signal-to-noise ratio. Whichever tool is used to model EMI hazards, the uncertainty in positional accuracy should be factored into the analysis. Positional uncertainties can be reduced to apparent uncertainty as viewed from the receiver. Using such data, not only should the predicted position be analyzed, but also any of the reasonably expected positions about the nominal position should be examined to eliminate the threat from electromagnetic impingement.

Volume V – Ionizing Radiation Hazards

1. Introduction

There have been several spacecraft vehicles that have used nuclear power to generate electricity over the past thirty to forty years. Power sources such as the two Radioisotope Thermoelectric Generators (RTG) on the Galileo spacecraft are common in the U.S. and the former U.S.S.R. space programs. In addition, nuclear reactors have been used in space. Whenever NASA seriously contemplates missions back to the Moon or to Mars or beyond in economical ways (with reuse potential), nuclear power, although controversial, is usually considered. The U.S.S.R. and subsequently the Russian Federation (RF) have used at least two types of nuclear reactors in space. The first Russian reactor, introduced in the 1960s, was known as the Romashka. The second reactor, called Topaz, followed and is still in use. The Russian Radar Ocean Reconnaissance Satellites (RORSATs) are also powered by nuclear reactors.

Either when nuclear power is used with small radioactive source materials for electrical power generation or when it is used with larger nuclear power reactor radioactive source materials, these nuclear materials could potentially return to Earth intact, spreading hazardous radioactive debris around the impact site. In addition, these satellite systems could collide with a piece of space debris or a meteoroid during launch or while on-orbit and produce radioactive debris that could randomly reenter over a wide geographical area. After using nuclear reactor powered systems in orbit, the RF normally boosts the satellite's reactor core (fuel-containing sections) section into a high orbit, where it will remain safe for hundreds of years. The primary high-level radiation source material hazard for these systems is Plutonium-238 which has a radioactive half-life of 87.8 years. As discussed below, these radiation hazards and the risks associated with them must be carefully evaluated and mitigated. If the spacecraft malfunctions in low orbit, the core can normally be separated from the reactor vehicle so it will vaporize during reentry, diluting the radioactive material over a large region of the atmosphere. In the case of RF's Cosmos 954 accident in 1978, neither a boost maneuver to high orbit nor core/reactor separation had taken place. Consequently, the spacecraft reentered the atmosphere largely intact over Canada, bringing harmful radioactive debris with it. The clean-up of this event cost the Canadians an estimated $14 million. The U.S. has launched several spacecraft with RTG and thus far no known radioactive debris cleanup operations have been necessary.

1.1 Radiation Hazards

As described above, radiation from nuclear materials in space systems can originate from nuclear power sources that vary in size and mass. In addition to power generation sources, nuclear materials from small-mass radioactive sources are used for measurement or calibration of experimental and operational space systems. In addition, radioactive materials may be created through activation by high-energy particle beams also used in space experiments. Since nuclear source material radiation (commonly called ionizing radiation) is natural to the environment of man, both on Earth and in space, its size and mass are important from a radiation hazard risk analysis viewpoint.

In the earth and space environments, there are two classes or ionizing radiation hazards – internal and external – that interact with both inorganic and organic material in biological as well as physical electronic systems. These ionizing radiation hazards are created by emissions from radioactive source materials that commonly consist of neutrons, alpha particles, beta particles, and gamma rays. Internal radiation sources are hazardous only when breathed or inhaled because they deposit their energy over short ranges. E.g., beta particles have limited penetrating ability with typical ranges in air up to about ten feet and in human tissue, the same beta particle would travel only a few millimeters. Alpha particles have an even shorter range. External radiation hazards are emissions such as x-rays and gamma rays that

deposit their energy over ranges longer than internal sources and can therefore affect electronic as well a biological systems over a greater range.

These emissions are at energy levels sufficient to remove an electron from the atom -- thus creating an *ionized* atom. This is the avenue through which energy is transferred from radiation to matter. When living organic material is irradiated with ionizing radiation, the amount of energy deposited in the biological system *as well as* the radiation's associated relative biological effectiveness (RBE) must be evaluated to assess the overall health risk. Non-ionizing radiation only excites the electrons around the nucleus causing heating effects of the material and, in the quantities found in communication satellite systems, is considered low health risk.

Ruling out a nuclear detonation in space, the major concern is exposure of humans to ionizing radiation, primarily through the reentry and breakup of spacecraft containing radioactive materials. If inadvertent reentry into the Earth's atmosphere occurs, the system may or may not survive intact until impact depending on the materials of construction. If the system containing large amounts of radioactive material survives reentry essentially intact, it may break up on impact, creating a debris plume spreading hazardous radioactive fragments and particles into surface winds and water.

In addition, there is concern for gamma ray emissions to spacecraft that approach too close to another spacecraft containing a nuclear reactor. Transient interference/interruption and in some cases damage can occur to delicate sensors and electronic devices. Gamma ray interference from orbiting Russian Federation reactors may occur from close encounters since current space power reactors use only payload shadow shielding. Interference may be due to gamma rays, neutrons and other associated emissions from the reactor core. Future U.S. spacecraft may require nuclear reactor power sources, and it is incumbent upon the U.S. to ensure that their use does not cause damage to other operational satellites. It is important to assess the relevant radiation and electrical quantities on satellite vehicles to insure minimal mission risk.

1.2 Radioactive Materials

For a description of radioactive materials used for electrical power generation from smaller thermo-electric sources up to larger nuclear reactors and their radioactive materials, see reference[16].

2. Design Considerations

For Air Force launches of nuclear power sources, responsibilities for participation in the Interagency Nuclear Safety Review Panel (INSRP) are specified in AFR 122-15, Nuclear Power System Safety Reviews and Surveys. Minor radioactive sources do not require the same level of review prior to launch. Within the Air Force, responsibilities are assigned by Air Force Regulation 122-16, Nuclear Safety Review Procedures for Space or Missile Use of Radioactive Sources. This regulation places centralized responsibility for coordinating the review with the Directorate of Nuclear Surety located at Kirtland Air Force Base.

Designers must also follow Nuclear Regulatory Commission and Environmental Protection Agency (EPA) standards and regulations designed to protect the health and safety of the general public.

[16] Space Applications of Radioactive Materials, prepared by SRS Technologies, prepared for Office of Space Commercial Space Transportation, June 1990.

3. Operational Steps to Minimize Risk

A broad range of design considerations and operational steps to minimize risks from radiation are the same as those covered under the previously discussed in Volume I - Collision Hazards. *Launch and Recovery Area Hazards to the Spacecraft* covers general safety procedures that can reduce exposure risk during launch. *Avoiding Collisions with Tracked Objects during Launch* is appropriate to planning launch and orbit insertion of a spacecraft containing radioactive materials, or to establishing a keep-away distance from one already on orbit. *Hazards from Meteoroids and Orbital Debris* is appropriate to the extent that the same analysis tools and procedures are required. *Hazards from Reentering Objects* is especially appropriate as it deals with mechanics by which space-based, radioactive materials can become a hazard to humans and our environment. A space launched reactor fueled with enriched Uranium-238 remains relatively benign with respect to the production of thermal and ionizing radiation until the fission process is initiated. The requirements for shielding are at their minimums, and the radiation protection and heat dispersion measures will not see their design loads until the vehicle has reached orbit and the reactor is activated. Radiation from the fission process may begin to activate previously inert materials in the structure of the reactor (generally at low levels). Therefore, given the risk of launch failure and debris spread as a result of such failure, the on-orbit reactor activation is an effective safety measure[17].

4. Assessment Tools

The Atmospheric Release Advisory Capability (ARAC) is a major real-time analysis capability for routine or emergency use. ARAC is a DoE-sponsored emergency response service providing real-time prediction of dose levels and extent of surface contamination from a broad range of possible events (accidents, spills, extortion threats involving nuclear material, re-entry of nuclear-powered airborne radioactive material. ARAC has responded to situations such as the Titan II missile accident in Arkansas and the re-entry of USSR's COSMOS-954.

ARAC currently supports emergency-preparedness plans at 50 DoD and DoE sites within the U.S. and also responds to accidents that occur elsewhere. The main ARAC center, at Lawrence Livermore National Laboratory (LLNL), is the focal point for data acquisition, data analysis, and assessment during a response, using a computer-based communication network to acquire real-time weather data and other pertinent data from the accident site and surrounding region.

Information from remote users, along with detailed weather data for the surrounding area obtained from the U.S. Air Force Global Weather Central, feeds directly into the ARAC central computer system at LLNL.

[17] See reference above to the 1990 source.

Volume VI – Chemical Hazards

1. Introduction

Chemical hazards include all substances (solids, liquids or gases) that have a potential to react negatively with a spacecraft or present an environmental concern. Hazardous chemicals released in orbit can present a hazard to other spacecraft. If the released substance is a solid, the risk of collision damage will probably override any other concerns. If it is a gas or liquid, then, in addition to the collision hazard, corrosion, sensor interference, and other physical effects are of concern. Corrosive chemicals released as exhaust from orbital maneuvering or as the result of an on-orbit explosion, either planned or unplanned, can degrade thermal control surfaces and destroy the coatings or optical sensors. Sources of spacecraft contamination routinely examined by the aerospace industry include materials of outgassing, particulates, propulsion-system interaction, overboard venting, debris, and atomic oxygen/ambient atmosphere interaction.

Spacecraft constructed with or containing toxic material causes a concern in the area of environmental effects on the atmosphere from residue of materials consumed by the heat of reentry. See Table VI-1 for an example list of on-board hazardous materials from the recent Wideband Gapfiller System Environmental Assessment (2000). Satellites that burn up during reentry produce vapors containing oxides of metals, solar cell material, insulation, and toxic fluids. These materials may stay in the stratosphere or troposphere for long periods of time and contribute to atmospheric pollution. Fortunately, many propellants are chemically unstable, degrade in a short period of time, and are therefore of less concern.

Degradation of contamination-sensitive systems and surfaces on most currently deployed GEO spacecraft has been graceful and consistent with current contamination models. The degradation attributable to contamination is due largely to self-contamination effects, i.e., the largest contamination and chemical hazards to most spacecraft appear to their own outgassing materials and propulsion sources. The possible contamination from other spacecraft does not appear to be noticeable.

Table VI-1

Materials On-Board Satellite[18]	Estimated Quantity per Satellite (lbs)
Anhydrous ammonia	600
Beryllium	Trace
Hydrazine	1000
Monomethylhydrazine	1000
Nickel metal hydride	trace
Potassium hydroxide	trace
Nitrogen tetroxide	1600
RDX/diphenylamine/nitro-cellulose	trace*
Zirconium	trace
Potassium perchlorate	trace
Iridium	trace

*a solid rocket propellant mix which can detonate

[18] Reference: Environmental Assessment, U.S. Air Force Wideband Gapfiller Satellite Program, Dept. of Air Force, HQ SMC, October 23, 2000

2. Design Considerations

Eliminating or avoiding most chemical hazards requires basic system engineering and design tasks that are well integrated into the development program. End-of-Life disposal considerations and subsequent environmental concerns should be carefully analyzed in program trade-offs and decision-making.

Fuels should be selected to minimize potential contamination during all mission phases. This includes planning fuel loads to eliminate residual fuel in spent stages and orbiting platforms. It is now an Air Force and U.S. Government policy that all on-board sources of stored energy of a spacecraft or upper stage shall be depleted when they are no longer required for mission operations or post-mission disposal. It is required that all propellant depletion burns shall be designed to minimize the probability of subsequent accidental collision and to minimize the impact of a subsequent accidental explosion.

Test programs involving the deorbit of spent stages or spacecraft should be carefully designed to minimize environmental contamination.

The following are Air Force/DoD/industry standard tools or documents, with which the debris mitigation handbook user should be familiar:

a) The Hazardous Materials Management Plan for the satellite system should identify all hazardous or toxic materials used in the production and operation of the satellite and launch vehicles upper stages. (A requirement in most Air Force programs and an industry standard).

b) Per DoD 5000.2R, a Programmatic Environmental Safety and Health Evaluation (PESHE) is required. The PESHE identifies ESH considerations for the lifetime of the system (including end of life disposal). It also identifies the Hazardous Materials Management Plan and Pollution Prevention measures.

c) The National Environment Policy Act (NEPA) documentation for the program. The Environmental Assessment or Environmental Impact Statement will analyze hazardous materials, potential impacts and alternatives.

3. Operational Steps to Minimize Risks

Minimizing release or spread of hazardous chemicals, metals, and other substances should be carefully planned and controlled. Options that must be considered for vehicles that have completed their mission include:

a. Parking in defined disposal orbit,
b. Parking in defined orbit for subsequent recovery,
c. Sending into deep space, or
d. Dispose through controlled, intact reentry into a safe area.

Typically, spacecraft are modeled physically, and various forms of breakup and explosion models are combined with propagation models to describe safety critical events/situations. Operational procedures and contingency plans are then written to avoid the events/situations or to mitigate hazardous chemical effects if they occur.

4. Assessment Tools

Careful selection and ground processing is used to limit the outgassing of spacecraft materials. Low outgassing materials are required to have a total mass loss of 1.0% of its total mass when heated in vacuum. For example, the total DSP satellite weight is 5100 lbs. About 20% of this mass, or roughly

1000 lbs, is organic, nonmetallic material. In a worst-case estimate, 1%, or about 10 lbs, of material would be lost by outgassing over a ten-year period, which is not a large amount of chemical material. A similar analysis can be performed concerning thruster fuels and their expenditure over a ten-year life. Certain ground-based and space-borne science experiments occasionally report observations of anomalous spectra that might be attributable to dumped thruster fuels, but no conclusive studies have been published. There had been many observations of possible self-contamination for the Russian space station Mir. Primarily, these observations involved darkened or clouded thermal control surfaces due to fluid leakages and planned releases. For GPS, the solar power production capability of GPS Block I and Block II satellites is currently degrading at a rate faster than that predicted by radiation models. Two years of data from calorimeters placed at two locations on a GPS Block IIR solar array strongly suggest that spacecraft self-contamination and poorly designed venting are responsible.

Volume VII – Hazards from Natural Phenomena

1. Introduction

This section describes the natural hazards arising from the effects of radiation and charged particles in the ionosphere or space plasma environment. These hazards are effective at high altitudes, and result mainly from interactions with environmental effects (rays, particles, etc.) that cannot penetrate deeply into the atmosphere.

The space environment considered surrounds the Earth, and is usually subdivided into three regions:

a. The Ionosphere – A region extending upward from about 80 km to 400 km altitude. Low-density gases in a moderately high state of ionization characterize this region. The ionizing mechanisms are mostly related to radiation originating at the Sun.
b. The Magnetosphere – A region surrounding the Earth, extending from the ionosphere to altitudes beyond 50,000 km. It is characterized by intense fluxes of very energetic ions and electrons; and exhibits extremely dynamic changes over periods from minutes to days.
c. Interplanetary Space – This region extends from the Earth to the edges of the solar system. The predominant environmental influences originate on the Sun.

Their effects on spacecraft organize the following natural hazards, since similar hazards may be encountered in several regions of space.

2. Hazards from Radiation and Energetic Particles

A magnetosphere and radiation belts surround the Earth. Energetic particles are always present with energies up to many million electron Volts. At altitudes below 120 km, particles lose energy and are attenuated rapidly in the atmosphere, so that only small numbers of extremely high-energy cosmic rays can get below 60 km. Energetic particles can cause physical damage to materials and electronic components; the level of damage is related to the time-integrated flux or fluence. These particles also interfere with on-board electronic processes, causing “rate” effects; the level of interference is related to the peak instantaneous flux. An important mechanism of physical damage is through formation of defects in crystalline semiconductor materials. This occurs when an energetic particle deposits its energy while passing through the material. An important interference mechanism is production of single event upsets, caused by deposition of an electrical charge in the vicinity of a semiconductor gate, and the subsequent temporary (or permanent) change in the computer stored data.

3. Hazards from Spacecraft Charging

Charging of an object in space occurs whenever there is an imbalance between the flow of positive and negative particles. Electrical charging generally involves a broad spectrum of the particle energy from zero to many thousands of electron Volts (eV). Spacecraft may charge to potentials as high as 20,000 volts in geosynchronous orbit, and 2000 volts in the auroral zones. Charging of a spacecraft to a high potential would be of little concern if the entire system were at a single potential. The serious hazards arise from differential charging. Large potential differences between spacecraft components can lead to arc breakdown, which in turn damages insulating materials. The breakdown also produces electromagnetic radiation that can couple to electronic devices in the spacecraft. Electrical charging can also lead to mechanical stresses in sensitive components, which is highly specific to particular components.

Since 1979, the Spacecraft Charging at High Altitudes (SCATHA) experiment has examined contamination derived from charged spacecraft. The charging of spacecraft results from magnetic storms. This, in turn, can cause ionized, outgassed molecules to return to the spacecraft. This phenomenon is called electrostatic reattraction (ESR). Today, a combined 20 years of data has been collected from six spacecraft charging experiments. These data have been used to assess ESR contamination effects for new spacecraft in various orbits. Overall, the data suggest that ESR contributes only 10% -12% of the total contamination impact.

4. Hazards from Plasma Interactions

The environment above 50-km altitude is in a high state of ionization, mainly because of low neutral particle densities and the prevalence of energetic solar radiation. A spacecraft usually carries with it an enhanced plasma wake. The ionized plasma that results is subject to generation of electromagnetic disturbances and waves. These may result in interference with electronic systems. The motion of a spacecraft in magnetized plasma also induces electric fields and currents in the spacecraft that may be troublesome for large spacecraft.

5. Contamination Hazards

Contamination of a spacecraft usually occurs when launch, deployment, or operational procedures result in the release of substances that do not escape freely to space. Some releases are intentional; others may follow a failure to maintain clean assembly and launch procedures. One particular contamination hazard is due to deterioration of paints and coatings on the surface. That deterioration may release microscopic particles. Substances released by one system, e.g., thrusters, may be deposited on another system, where they can be detrimental to its performance. Other important sources of contamination are: (1) outgassing from substances carried on the rocket or launch system, (2) particulates released by vibrations in the launch environment, and (3) atmospheric gases and vapors that collect on a spacecraft on the launch pad and perhaps during its ascent.

6. Hazards During Extra-Vehicular Activity

NASA is ultimately responsible for ensuring the safety of their astronauts. However, NASA astronauts do support Air Force satellite programs and all agencies have an obligation to ensure that missions involving astronauts or that could affect astronauts are carefully planned and executed in order to minimize the risk to them.

While astronauts require protection against many hazards, several types of hazards have been identified as particularly consequential. Humans are extremely vulnerable to penetrating radiation and energetic particles. Energetic particles released by solar flares pose an especially severe hazard. Astronaut safety must also be considered in all space operations, where one or more constituents of the environment can induce unanticipated hazards.

Appendix B – Example Orbital Reentry Debris Risk Analysis for a Delta II Stage 2

In January of 1997, a propellant tank and a spherical, helium tank from the second stage of a Delta II launch vehicle were found in Georgetown, TX and Seguin, TX, respectively. It was later determined that these objects were from an MSX Air Force mission launched in the previous year. In April of 2000, the same types of objects, tanks from the second stage of a Delta II, were observed plummeting to the ground from high altitude near Cape Town, South Africa. The propellant tank impacted on the outskirts of Durbanville, SA and the helium tank landed near Worcester, SA. As with many spent stages of launch vehicles and satellites that are no longer functioning, the orbit of the Delta Stage 2 is allowed to decay naturally. Thus, the stage randomly reenters the earth's atmosphere within its orbital plane experiencing a high degree of aerodynamic heating on its plunge through the upper atmosphere. The events in Texas and South Africa are evidence that the Delta Stage 2 breaks apart with the propellant tank and helium tanks surviving reentry and therefore posing a hazard to humans.

The magnitude of such a hazard (i.e. risk) is determined by the number, size and weight of the surviving debris objects and where on the surface of the earth they land. Risk is measured by a quantity known as "casualty expectation" (E_C). It is a function of the probability of an incident occurring and the consequence of the incident. For reentering space objects E_C is calculated as the product of the probability of impacting debris in a region (P_{Ii}), the population density of that region (D_i), and the casualty causing area of the surviving debris (A_C) summed over all regions at risk.

Note that casualty expectation addresses persons and not an individual. That is to say that the E_C

$$E_C = \sum_i P_{I_i} D_i A_C$$

calculation applies to the total population at risk rather than to each individual within that population. Therefore casualty expectation is sometimes referred to as "collective risk". The risk to an individual can be calculated by dividing the casualty expectation figure by the number of persons in the population.

To quantify the risk posed by the Delta Stage 2, a reentry/breakup and risk analysis is performed. It consists of the following two parts: 1) a breakup analysis to determine the survivable objects; and 2) an estimate of the casualty expectation associated with those objects.

1. Reentry Heating Calculation

The first step is to understand the basic construction of the reentering object, and the material and dimensions of its primary components. It is known that the structure/miniskirt, and equipment panels of the Delta II Stage 2 (shown below) are mostly aluminum. The fuel/oxidizer tank is stainless steel, the helium/nitrogen spheres are titanium, the engine nozzle is a carbon composite, and the nozzle extension is Niobium.

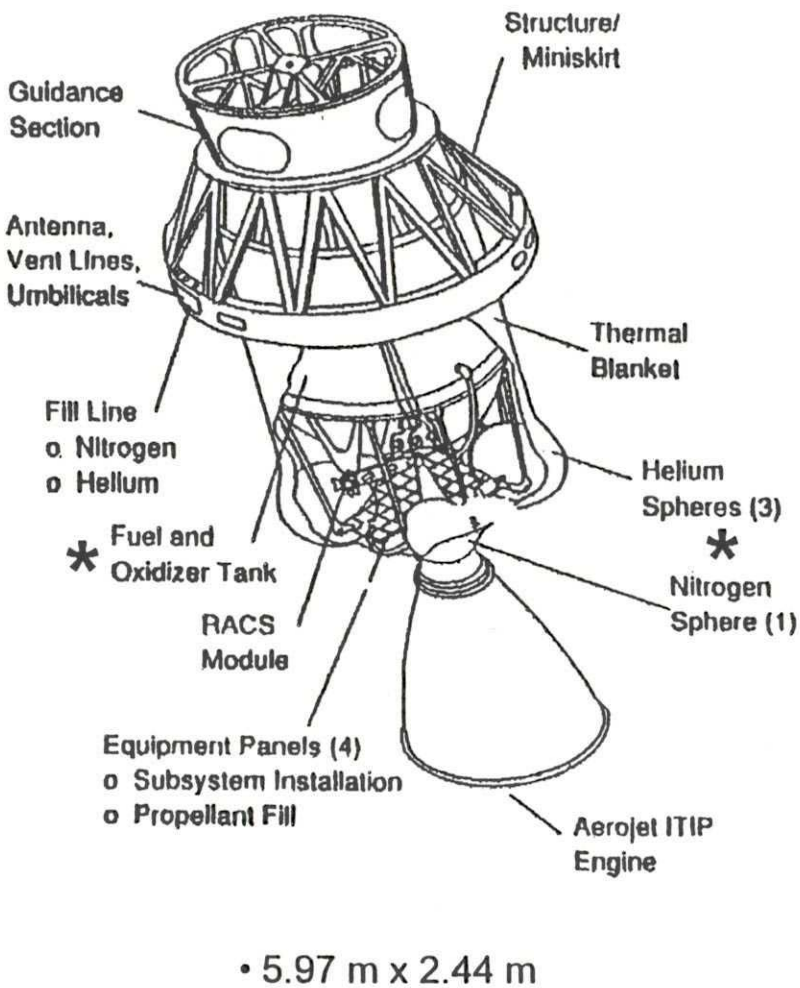

Figure 1. Delta II Stage 2.

We wish to estimate the structural heating and breakup altitude for the reentering Stage 2 body from the MSX mission. Initializing the vehicle at a low orbital state and assuming a ballistic coefficient of 32 lb/ft^2, and then integrating the equations of motion produced a reentry trajectory simulation. The breakup altitude is assumed to be the altitude at which the thin-walled aluminum primary structure passes through the melt temperature of aluminum (933 K.)

The heat content, Q, of the body (which is treated as a single lump) changes with time as

$$\dot{Q} = \left(k_2 \dot{q}_s - \varepsilon \sigma T_m^4\right) A_w \tag{1}$$

where $\dot{q}_s$ is the stagnation heat flux, T_m is the bulk body temperature, and A_w is the wetted area of the body through which heat flows. The factor k_2 is an area-averaging factor analogous to f_c in the MORSAT/ORSAT codes of NASA. The surface emissivity is denoted by ε. For tumbling bodies of common shape, we have found that reentry data are best matched by choosing $k_2 = 0.12$ and $\varepsilon = 1.0$.

Denoting the mass of the body by m and its specific heat by c_m, the heat content can be written as

$$\dot{Q} = m\, c_m\, \dot{T}_m$$

or

$$\dot{Q} = \rho_m\, V_m\, c_m\, \dot{T}_m \tag{2}$$

where ρ_m and V_m are the material density and volume, respectively.

Substituting (2) into (1) gives

$$\dot{T}_m = \frac{k_2\, \dot{q}_s - \varepsilon\, \sigma\, T_m^4}{\rho_m\, c_m\, \tau} \tag{3}$$

where τ is the ratio of volume to wetted area, i.e., an equivalent thickness.

The stagnation heat flux (see Ref. 1) is given by the following expression

$$\dot{q}_s \left(\mathrm{Btu/ft^2/sec}\right) = 17{,}600 \sqrt{\frac{R_{ref}}{R}} \sqrt{\frac{\rho_\infty}{\rho_{ref}}} \left(\frac{V_\infty}{V_{ref}}\right)^{3.15} \left(\frac{T_s - T_m(t)}{T_s - T_{ref}}\right) \tag{4}$$

where T_s is the instantaneous flight stagnation temperature and the various reference values are

$$R_{ref} = 1\,\mathrm{ft},\ \rho_{ref} = 2.3769\mathrm{x}10^{-3}\,\mathrm{slug/ft^3},\ V_{ref} = 26{,}000\,\mathrm{ft/sec},\ T_{ref} = 540°R \tag{5}$$

Equation (3) was integrated along the Delta Stage 2 reentry trajectory with aluminum material properties input

$$\rho_m = 168.56 \text{ lbm} / \text{ft}^3$$
$$c_m = 0.215 \text{ Btu} / \text{lbm} / {}^\circ R$$

and the following assumed values for body radius, thickness, and initial temperature.

$$R = 2.875 \text{ ft}$$
$$\tau = 0.050 \text{ in}$$
$$T_m(0) = 300 \text{ K} = 540^\circ R$$

The emissivity and area averaging parameter were set to

$$\varepsilon = 1$$
$$k_2 = 0.12$$

The computed material temperature, as a function of altitude, is shown in Figure 2 below. This plot shows that breakup should occur at 43 nm, where T_m moves through 933 K, the melt temperature for aluminum.

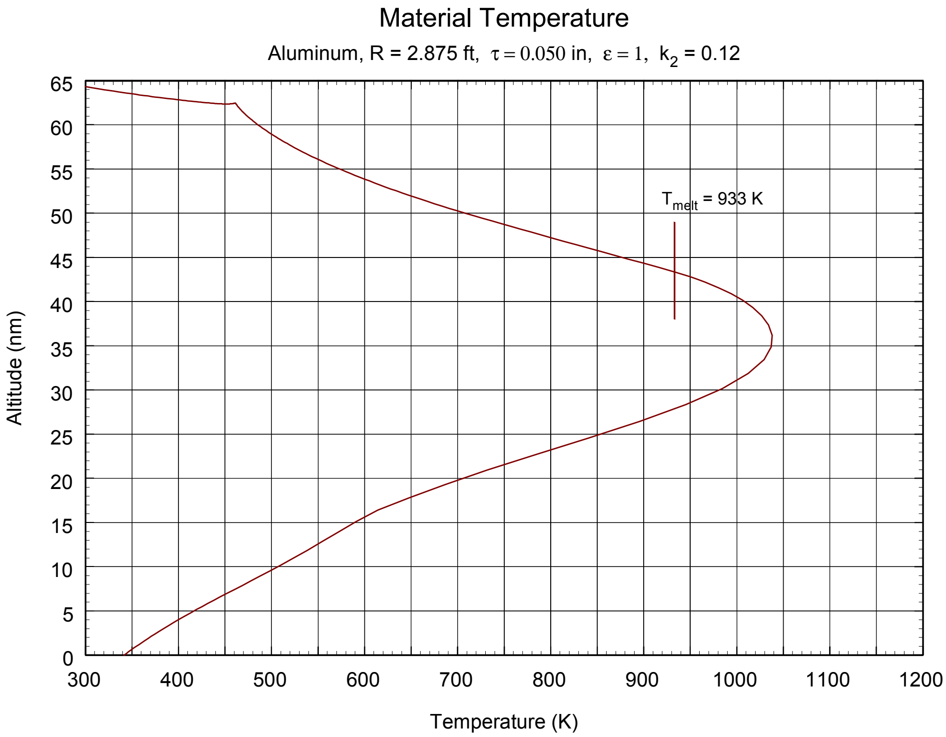

Figure 2. Material Temperature of Delta II MSX Stage 2 Structure as a Function of Altitude. Breakup Occurs at 43 nm.

Note that the structure heating peaks out at about 1040 K, far short of the 1670 K temperature required to melt stainless steel, or the 1943 K melting temperature of titanium. The composite material of the engine nozzle would likely sublime at an even higher temperature. Therefore, the reentry heating analysis predicts that the Delta Stage 2 propellant tank, the titanium helium tanks, as well as the composite nozzle all survive to surface impact. The Niobium nozzle extension melting point is 2,741K, which suggests this will also survive re-entry.

2. Casualty Expectation Calculation

For a random reentry of a space object, the inclination (i) of the orbit determines the latitude region exposed to the hazard. Impact can occur only at latitudes in the range $-i$ to i. The stage from the MSX mission was at an inclination of 38 deg.

A population density model can be constructed into one-degree latitude bands from the Gridded Population of the World (GPW) dataset accessed via the Center for International Earth Science Information Network (www.ciesin.org). This dataset is a product of Reference 2 and needs to be scaled-up slightly to reflect the current estimated global population of just over 6 billion persons.

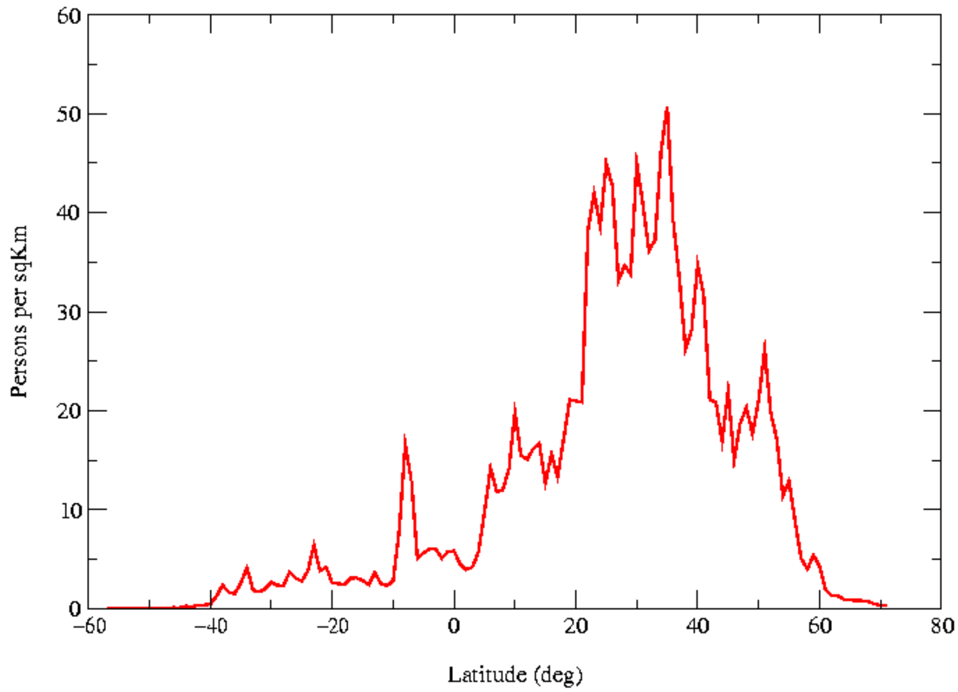

Figure 3. World Population Density by Latitude

The probability of debris impact for any given narrow latitude band is generally approximated according to the dwell time over that latitude band relative to the orbit period. The casualty area from debris impact is assumed to be constant for any reentry location. Therefore, multiplying the population density for each latitude band with the dwell time ratio and then summing over all populated latitudes within the inclination of the orbit produces an expected casualty per debris casualty area, E_C/A_C.

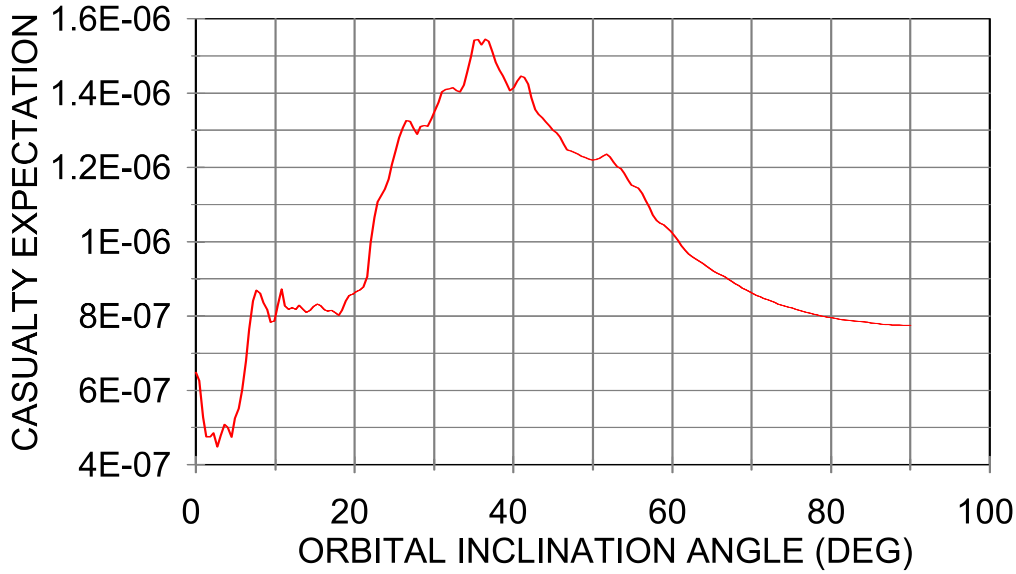

Figure 4. Casualty Expectation per 1 ft^2 of Effective Debris Area of Impacting Debris as a Function of Orbital Inclination of the Reentering Object

The casualty expectation function shown above was developed from explicit equations for debris impact density and population density (see Ref. 3).

Once the components are identified, a casualty area for each individual fragment is calculated by taking the cross-sectional area of the fragment and adding a human risk border of 1 ft. (0.3 meters). The total casualty area is determined by summing over all the individual fragments. In many cases the exact dimensions are unknown, but cross-sectional estimates are available and are then combined with a human area to get an A_C. For inert, reentry debris, all impacts are assumed to be from a nearly vertical angle and no secondary effects, such as ricocheting or skidding are considered. The total casualty-causing area of the debris provides an efficient way to quantify the entire break-up of the reentering spacecraft into a single value.

When dimensions for each surviving component are defined, a 1 ft. human border (equal to 2 ft. added to length and width) is attached to each fragment's rectangular cross-section. In the case of spherical or cylindrical objects, a 1 ft. human radius is added to the object radius and a circular area calculated. For cylinders, the final individual A_C is taken as the larger of the circular and rectangular cross-sections.

where

l_{fn} & w_{fn} are the length and width of fragment n
r_h is the radius of "standard human" (1 ft)
r_{fn} is the radius of fragment n

In most casualty analyses, all persons are assumed to be standing outdoors, unprotected from any type of shelter. This is a conservative assumption and not unreasonable when considering heavy fragments with high terminal velocity, because most sheltering would collapse in such cases. However, in many cases, the inventory of survivable components of the satellite shows that much of the debris is of rather small size. Therefore, sheltering could have a significant effect on the impact consequence. There is a simple

technique for incorporating sheltering into the collective risk calculation. It is called a "Weighted Effective Casualty Area" approach and is described in Reference 4, a report prepared for the Department of Transportation in 1992. The approach is as follows:

Three levels of protection are considered:
Type 1: Buildings with concrete or reinforced roofs.
Type 2: Single story buildings such as houses or trailers.
Type 3: Unsheltered (no protection).

Kinetic energy (KE) levels at impact are calculated; thresholds for injury to a person located within such type of protection are:
Type 1: Minimum KE (for onset of risk) = 6200 ft-lb
Maximum KE (for which the probability of casualty is unity) = 74,000 ft-lb
Type 2: Minimum KE = 100 ft-lb
Maximum KE = 3200 ft-lb
Type 3: KE for lethality > 35 ft-lb

Calculate kinetic energy at impact by

$$KE = m\beta\rho_{SL}$$

m is the mass of the object
β is the ballistic coefficient
ρ_{SL} is the atmospheric density at sea level

The distribution of people within the various types of protection has been estimated on a worldwide, around the clock, around the calendar basis as:

Type 1 Protection: 20%
Type 2 Protection: 70%
Type 3 Protection: 10%

The weighting, according to kinetic energy at impact, is then applied to each fragment's casualty area prior to summing for the total casualty area. It is felt that this sheltering technique gives a more precise evaluation of the risk. The following table estimates the effective casualty area for each surviving object.

Delta Stage 2 Survivable Components						
Item (#)	Material	Wt (lb)	Ballistic coefficient (lb/ft^2)	Dimen-sion (ft)	K.E. (ft-lbs)	Casualty Area (ft^2)
Prop tank (1)	Stainless steel	531	15	9.0 x 5.7	100,000	72.4
Large sphere (2)	Titanium	67	25	Dia = 1.9	22,000	10.3 (2)
Small sphere (2)	Titanium	22	17	Dia = 1.4	4900	7.0 (2)
Nozzle throat (1)	Composite	60	3	1 x 2	2300	22.6
Nozzle extension	Niobium	54	0	~ 4.0 x 1.3	0	0
					A_C =	129.6

Then, according to the equation for E_C and Figure 4, the estimated casualty expectation for a Delta II Stage 2 random reentry is 1.9E-04 or 2 in 10,000. Empirical evidence suggests that the Niobium nozzle portion does not survive re-entry. This decreases Ac to ~109 square feet. Furthermore, since all aluminum attach hardware is melted, these components become separate, and should each have their own casualty expectation estimate. Lumping the entire second stage together is inaccurate.

References

1. R. W. Detra, N. H. Kemp, and F. R. Riddell, *Addendum to Heat Transfer to Satellite Vehicles Re-entering the Atmosphere,* Jet Propulsion, December 1957, p. 1256.

2. W. Tobler, U. Deichmann, J. Gottsegen, & K. Maloy, *The Global Demography Project*, Technical Report TR-95-6, Dept. of Geographic Information and Analysis, Univ. of Calif., Santa Barbara, April 1995.

3. R. Patera, *Casualty Expectation for Reentering Spacecraft*, The Aerospace Corp. IOC# A96-5447.3-4, 7 February 1996.

4. O. Refling, R. Stern, & C. Potz, *Review of Orbital Reentry Risk Predictions*, The Aerospace Corp., Report No. ATR-92(2835)-1, 15 July 1992.

Appendix C - Acronyms and Abbreviations

AAS	American Astronautical Society
AF	Air Force
AFI	Air Force Instruction
AFMC	Air Force Material Command
AFR	Air Force Regulation
AFRL	Air Force Research Laboratory
AFRL/DEL	Missile Assessment Center
AFRL/DELE	Laser Effects Test Facility
AFSCN	Air Force Satellite Control Network
AFSPC	Air Force Space Command
AFTO	Air Force Technical Order
AIAA	American Institute of Aeronautics and Astronautics, Inc.
ANSI	American National Standard Institute
ARAC	Atmospheric Release Advisory Capability
ARAR	Accident Risk Assessment Report
ARCM	Atlas Roll Control Module
ATR	Aerospace Technical Report
BER	Bit Error Rate
BLE	Ballistic Limit Equations
CALIPER	CMOC COLA software tool
CCAM	Contamination and Collision Avoidance Maneuver
CDR	Critical Design Review
CDRL	Contract Data Requirements List
CM	Centimeter
CMOC	Cheyenne Mountain Operations Center
COIL	Chemical Oxygen Iodine Laser
COLA	Collision Avoidance
Collision Vision	Aerospace Corporation COLA software tool
COMBO	Computation of Miss Between Objects
CORDS	Center for Orbital and Reentry Debris Studies
CW	Continuous Wave
Deg	Degrees
DMSP	Defense Meteorological Satellite Program
DoD	Department of Defense
DoDD	Department of Defense Directive
DoDI	Department of Defense Instruction
DoE	Department on Energy
DSCS	Defense Satellite Communications System
EELV	Evolved Expendable Launch Vehicle
EMI	Electromagnetic Interference
EOL	End-of-Life
EPA	Environmental Protection Agency
ER	Eastern Range
ESA	European Space Agency
ESD	Electrostatic Discharge
ESH	Environmental Safety and Health
ESOC	European Space Operations Center

ESR	Electrostatic Reattraction
eV	Electron Volts
FAA	Federal Aviation Administration
FCC	Federal Communications Commission
GEO	Geosynchronous Orbit
GPS	Global Positioning System
GPW	Gridded Population of the World
GSFC	Goddard Space Flight Center
GTO	Geostationary Transfer Orbit
HQ	Headquarters
HP	High Precision
IADC	Inter-Agency Space Debris Coordination
IG	Interagency Group
INSRP	Interagency Nuclear Safety Review Panel
ISS	International Space Station
ITRAL	Integrated Target Response Algorithm
IUS	Interim Upper Stage
JSC	Johnson Space Center
KE	Kinetic Energy
Kg	Kilogram
Km	Kilometer
LCH	Laser clearing House
LDEF	Long Duration Exposure Facility
LEO	Low Earth Orbit
LLNL	Lawrence Livermore National Laboratory
M	Meter
MEO	Medium Earth Orbit
MORSAT	Miniature Object Reentry Survival Analysis Tool
MRTFB	Major Range Test Facility Base
MSPSP	Missile System Prelaunch Safety Package
MSX	Mid-Course Space Experiment
NASA	National Aeronautics and Space Administration
NASA/TP	NASA/Technical Publication
NASDA	National Space Development Agency of Japan
NEPA	National Environmental Policy Act
NMI	Nautical Mile
NOAA	National Oceanic and Atmospheric Administration
NORAD	North American Air Defense Command
NPOESS	National Polar Orbiting Environmental Sensing System
NRO	National Reconnaissance Office
NROI	National Reconnaissance Office Instruction
ODM	NASA Orbital Debris Engineering Model
OOH	Orbital Operational Handbook
OPR	Office of Primary Responsibility
ORDEM	Orbital Debris Engineering Model
ORSAT	Object Reentry Survival Analysis Tool
OSS&E	Orbital Systems Safety and Effectiveness (plan)
PBV	Post-Boost Vehicle
PDR	Preliminary Design Review
PESHE	Programmatic Environmental Safety and Health Evaluation

RACS	Roll Attitude Control System
RADCAL	Radar Calibration
R/B	Rocket Body
RBE	Relative Biological Effectiveness
RF	Radio Frequency
RFI	Radio Frequency Interference
RORSAT	Radar Ocean Reconnaissance Satellite
RPHEL	Repetitively Pulsed High Energy Lasers
RSO	Resident Space Object
RTG	Radioisotope Thermo-Electric Generator
RV	Reentry Vehicle
SAB	Scientific Advisory Board
SAF/SA	Air Force Office of Space Policy
SCATHA	Spacecraft Charging at High Altitudes
SCC	Space Control Center
SMC	Space and Missile Systems Center
SMC/AX	Office of Specialty Engineering and Product Assurance
SMC/CV	Vice Commander’s Office
SMC/SE	Directorate of Safety Office
SMC/TE	Office of Space Test and Experimentation
SMC/XR	Office of Development Plans
SNR	Signal-to-Noise Ratio
SOPS	Space Operations Squadron
SP	Special Perturbations
SPADOC	Space Defense Operations Center
SPO	System Program Office
SRM	Solid Rocket Motor
SSN	Space Surveillance Network
SSO	Space Systems Operations
STK/CAT	Satellite Tool Kit/Collision Avoidance Tool
STS	Space Transportation System
TBD	To Be Determined
TBS	To Be Supplied
TR	Technical Report
TT&C	Telemetry, Tracking and Evaluation
USAF	United States Air Force
USSPACECOM	U.S. Space Command
USSR	Union of Soviet Socialist Republics
WR	Western Range